



Kageyama, M., Braconnot, P., Harrison, S. P., Haywood, A. M., Jungclaus, J. H., Otto-Bliesner, B. L., ... Zhou, T. (2018). The PMIP4 contribution to CMIP6 - part 1: overview and over-arching analysis plan. *Geoscientific Model Development*, 11(3), 1033-1057. <https://doi.org/10.5194/gmd-11-1033-2018>

Publisher's PDF, also known as Version of record

License (if available):
CC BY

Link to published version (if available):
[10.5194/gmd-11-1033-2018](https://doi.org/10.5194/gmd-11-1033-2018)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the final published version of the article (version of record). It first appeared online via European Geosciences Union at <https://doi.org/10.5194/gmd-11-1033-2018> . Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/pure/about/ebr-terms>



The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan

Masa Kageyama¹, Pascale Braconnot¹, Sandy P. Harrison², Alan M. Haywood³, Johann H. Jungclaus⁴, Bette L. Otto-Bliesner⁵, Jean-Yves Peterschmitt¹, Ayako Abe-Ouchi^{6,7}, Samuel Albani^{1,8}, Patrick J. Bartlein⁹, Chris Brierley¹⁰, Michel Crucifix¹¹, Aisling Dolan³, Laura Fernandez-Donado¹², Hubertus Fischer¹³, Peter O. Hopcroft^{14,15}, Ruza F. Ivanovic³, Fabrice Lambert¹⁶, Daniel J. Lunt¹⁴, Natalie M. Mahowald¹⁷, W. Richard Peltier¹⁸, Steven J. Phipps¹⁹, Didier M. Roche^{1,20}, Gavin A. Schmidt²¹, Lev Tarasov²², Paul J. Valdes¹⁴, Qiong Zhang²³, and Tianjun Zhou²⁴

¹Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

²Centre for Past Climate Change and School of Archaeology, Geography and Environmental Science (SAGES) University of Reading, Whiteknights, RG6 6AH, Reading, UK

³School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

⁴Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany

⁵National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO 80305, USA

⁶Atmosphere Ocean Research Institute, University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa-shi, Chiba 277-8564, Japan

⁷Japan Agency for Marine-Earth Science and Technology, 3173-25 Showamachi, Kanazawa, Yokohama, Kanagawa, 236-0001, Japan

⁸Institute for Geophysics and Meteorology, University of Cologne, Cologne, Germany

⁹Department of Geography, University of Oregon, Eugene, OR 97403-1251, USA

¹⁰University College London, Department of Geography, WC1E 6BT, UK

¹¹Université catholique de Louvain, Earth and Life Institute, Louvain-la-Neuve, Belgium

¹²Dpto. Física de la Tierra, Astronomía y Astrofísica II, Instituto de Geociencias (CSIC-UCM), Universidad Complutense de Madrid, Spain

¹³Climate and Environmental Physics, Physics Institute & Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

¹⁴School of Geographical Sciences, University of Bristol, Bristol, UK

¹⁵School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, UK

¹⁶Catholic University of Chile, Department of Physical Geography, Santiago, Chile

¹⁷Department of Earth and Atmospheric Sciences, Bradfield 1112, Cornell University, Ithaca, NY 14850, USA

¹⁸Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A7, Canada

¹⁹Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, TAS 7001, Australia

²⁰Earth and Climate Cluster, Faculty of Science, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

²¹NASA Goddard Institute for Space Studies and Center for Climate Systems Research, Columbia University 2880 Broadway, New York, NY 10025, USA

²²Department of Physics and Physical Oceanography, Memorial University of Newfoundland and Labrador, St. John's, NL, A1B 3X7, Canada

²³Department of Physical Geography, Stockholm University, Stockholm, Sweden

²⁴LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, P.O. Box 9804, Beijing 100029, China

Correspondence: Masa Kageyama (masa.kageyama@lsce.ipsl.fr)

Received: 1 May 2016 – Discussion started: 26 May 2016

Revised: 16 January 2018 – Accepted: 22 January 2018 – Published: 16 March 2018

Abstract. This paper is the first of a series of four GMD papers on the PMIP4-CMIP6 experiments. Part 2 (Otto-Bliesner et al., 2017) gives details about the two PMIP4-CMIP6 interglacial experiments, Part 3 (Jungclauss et al., 2017) about the last millennium experiment, and Part 4 (Kageyama et al., 2017) about the Last Glacial Maximum experiment. The mid-Pliocene Warm Period experiment is part of the Pliocene Model Intercomparison Project (PlioMIP) – Phase 2, detailed in Haywood et al. (2016).

The goal of the Paleoclimate Modelling Intercomparison Project (PMIP) is to understand the response of the climate system to different climate forcings for documented climatic states very different from the present and historical climates. Through comparison with observations of the environmental impact of these climate changes, or with climate reconstructions based on physical, chemical, or biological records, PMIP also addresses the issue of how well state-of-the-art numerical models simulate climate change. Climate models are usually developed using the present and historical climates as references, but climate projections show that future climates will lie well outside these conditions. Palaeoclimates very different from these reference states therefore provide stringent tests for state-of-the-art models and a way to assess whether their sensitivity to forcings is compatible with palaeoclimatic evidence. Simulations of five different periods have been designed to address the objectives of the sixth phase of the Coupled Model Intercomparison Project (CMIP6): the millennium prior to the industrial epoch (CMIP6 name: *past1000*); the mid-Holocene, 6000 years ago (*midHolocene*); the Last Glacial Maximum, 21 000 years ago (*lgm*); the Last Interglacial, 127 000 years ago (*lig127k*); and the mid-Pliocene Warm Period, 3.2 million years ago (*midPliocene-eoi400*). These climatic periods are well documented by palaeoclimatic and palaeoenvironmental records, with climate and environmental changes relevant for the study and projection of future climate changes. This paper describes the motivation for the choice of these periods and the design of the numerical experiments and database requests, with a focus on their novel features compared to the experiments performed in previous phases of PMIP and CMIP. It also outlines the analysis plan that takes advantage of the comparisons of the results across periods and across CMIP6 in collaboration with other MIPs.

1 Introduction

Instrumental meteorological and oceanographic data show that the Earth has undergone a global warming of $\sim 0.85^\circ\text{C}$ since the beginning of the Industrial Revolution (Hartmann et al., 2013), largely in response to the increase in atmospheric greenhouse gases. Concentrations of atmospheric greenhouse gases are projected to rise significantly during

the 21st century, reaching levels well outside the range of recent millennia. In making future projections, models are operating beyond the conditions under which they have been developed and validated. Changes in the recent past provide only limited evidence for how climate responds to changes in external factors and internal feedbacks of the magnitude expected in the future. Palaeoclimate states radically different from those of the recent past provide a way to test model performance outside the range of recent climatic variations and to study the role of forcings and feedbacks in establishing these climates. Although palaeoclimate simulations strive for verisimilitude in terms of forcings and the treatment of feedbacks, none of the models used for future projection have been developed or calibrated to reproduce past climates.

We have to look back 3 million years to find a period of Earth's history when atmospheric CO_2 concentrations were similar to the present day (the mid-Pliocene Warm Period, mPWP). We have to look back several tens of millions of years further (the early Eocene, ~ 55 to 50 million years ago) to find CO_2 concentrations similar to those projected for the end of this century. These periods can offer key insights into climate processes that operate in a higher CO_2 , warmer world, although their geographies are different from today (e.g. Lunt et al., 2012; Caballero and Huber, 2010). During the Quaternary (2.58 million years ago to present), Earth's geography was similar to today and the main external factors driving climatic changes were the variations in the seasonal and latitudinal distribution of incoming solar energy arising from cycles in Earth's orbit around the Sun. The feedbacks from changes in greenhouse gas concentrations and ice sheets acted as additional controls on the dynamics of the atmosphere and the ocean. In addition, rapid climate transitions, on human-relevant timescales (decades to centuries), have been documented for this most recent period (e.g. Marcott et al., 2014; Steffensen et al., 2008).

By combining several past periods, the credibility of climate projections can be assessed by using information about longer-term palaeoclimate changes that are as large as the anticipated future change. Replicating the totality of past climate changes with state-of-the-art climate models, driven by appropriate forcings (e.g. insolation, atmospheric composition) and boundary conditions (e.g. ice sheets), is a challenge (Braconnot et al., 2012; Harrison et al., 2015). It is challenging, for example, to represent the correct amplitude of past climate changes such as glacial–interglacial temperature differences (e.g. between the Last Glacial Maximum, LGM, $\sim 21\,000$ years ago, and the pre-industrial temperatures; cf. Harrison et al., 2014) or to represent the northward extension of the African monsoon during the mid-Holocene (MH, ~ 6000 years ago) (Perez-Sanz et al., 2014). Interpreting palaeoenvironmental data can also be challenging, particularly disentangling the relationships between changes in large-scale atmospheric or oceanic circulation, broad-scale

regional climates, and local environmental responses to these changes during climate periods when the relative importance of various climate feedbacks cannot be assumed to be similar to today. This challenge is paralleled by concerns about future local or regional climate changes and their impact on the environment. Therefore, modelling palaeoclimates is a means to understand past climate and environmental changes better, using physically based tools, as well as a means to evaluate model skill in forecasting the responses to major drivers.

These challenges are at the heart of the Paleoclimate Modelling Intercomparison Project (PMIP) and the new set of CMIP6-PMIP4 simulations (Otto-Bliesner et al., 2017; Jungclaus et al., 2017; Kageyama et al., 2017; Haywood et al., 2016) has the ambition of tackling them. Palaeoclimate experiments for the Last Glacial Maximum, the mid Holocene, and the last millennium were formally included in CMIP during its fifth phase (CMIP5, Taylor et al., 2012), equivalent to the third phase of PMIP (PMIP3, Braconnot et al., 2012). This formal inclusion made it possible to compare the mechanisms causing past and future climate changes in a rigorous way (e.g. Izumi et al., 2015) and to evaluate the models used for projections (e.g. Harrison et al., 2014, 2015). More than 20 modelling groups took part in PMIP3 and many of the PMIP3 results are prominent in the fifth IPCC assessment report (Masson-Delmotte et al., 2013; Flato et al., 2013). PMIP3 also identified significant knowledge gaps and areas where progress is needed. PMIP4 has been designed to address these issues.

The five periods chosen for PMIP4-CMIP6 (Table 1) were selected because they contribute directly to the CMIP6 objectives; in particular, they address the key CMIP6 question “How does the Earth system respond to forcing?” (Eyring et al., 2016) for multiple forcings and climate states different from the current or historical climates. They are characterized by greenhouse gas concentrations, astronomical parameters, ice sheet extent and height, and volcanic and solar activities different from the current or historical ones (Table 2). This is consistent with the need to provide a large sample of the climate responses to important forcings. The choice of two new periods, the Last Interglacial (LIG, $\sim 127\,000$ years ago) and the mid-Pliocene Warm Period, was motivated by the desire to explore the relationships between the climate–ice sheet system and sea level and to expand analyses of climate sensitivity and polar amplification. For each target period, comparison with environmental observations and climate reconstructions enables us to determine whether the modelled responses are realistic, allowing PMIP to address the second key CMIP6 question “What are the origins and consequences of systematic model biases?”. PMIP simulations and data–model comparisons will show whether or not the biases in the present-day simulations are found in other climate states. Also, analyses of PMIP simulations will show whether or not present-day biases have an impact on the magnitude of simulated climate changes. Finally, PMIP is also

relevant to the third CMIP6 question “How can we assess future climate changes given climate variability, predictability, and uncertainties in scenarios?” because the simulation of the last millennium’s climate includes more processes (e.g. volcanic and solar forcings) to describe natural climate variability than the *piControl* experiment.

The detailed justification of the experimental protocols and analysis plans for each period are given in a series of companion papers: Otto-Bliesner et al. (2017) for the *mid-Holocene* and *lig127ka* experiments, Kageyama et al. (2017) for the *lgm*, Jungclaus et al. (2017) for the *past1000*, and Haywood et al. (2016) for the *midPliocene-eoi400* experiment. These papers also explain how the boundary conditions for each period should be implemented and include the description of sensitivity studies using the PMIP4-CMIP6 simulation as a reference. Here, we provide an overview of the PMIP4-CMIP6 simulations and highlight the scientific questions that will benefit from the CMIP6 environment. In Sect. 2, we give a summary of the PMIP4-CMIP6 periods and the associated forcings and boundary conditions. The analysis plan is outlined in Sect. 3. Critical points in the experimental set-up are briefly described in Sect. 4. A short conclusion is given in Sect. 5.

2 The PMIP4 experiments for CMIP6 and associated palaeoclimatic and palaeoenvironmental data

The choice of the climatic periods for CMIP6 is based on past PMIP experience and is justified by the need to address new scientific questions, while also allowing the evolution of the models and their ability to represent these climate states to be tracked across the different phases of PMIP (Table 1). The forcings and boundary conditions for each PMIP4-CMIP6 palaeoclimate simulation are summarized in Table 2. All the experiments can be run independently and have value for comparison to the CMIP6 DECK (Diagnostic, Evaluation and Characterization of Klima) and historical experiments (Eyring et al., 2016). They are therefore all considered Tier 1 within CMIP6. It is not mandatory for groups wishing to take part in PMIP4-CMIP6 to run all five PMIP4-CMIP6 experiments. It is however mandatory to run at least one of the two entry cards, i.e. the *midHolocene* or the *lgm*.

2.1 PMIP4-CMIP6 entry cards: the mid-Holocene (*midHolocene*) and Last Glacial Maximum (*lgm*)

The MH and LGM periods are strongly contrasting climate states. The MH provides an opportunity to examine the response to orbitally induced changes in the seasonal and latitudinal distribution of insolation (Fig. 1). It is a period of strongly enhanced Northern Hemisphere summer monsoons, extra-tropical continental aridity, and much warmer summers. The LGM provides an opportunity to examine the climatic impact of changes in ice sheets, continental extent

Table 1. Characteristics, purpose, and CMIP6 priority of the five PMIP4-CMIP6 experiments. All experiments can be run independently. Calendar ages are expressed in Common Era (CE) and geological ages are expressed in thousand years (ka) or million years (Ma) before present (BP), with present defined as 1950.

Period	Purpose	CMIP6 priority
Last millennium (<i>past1000</i>) 850–1849 CE	(a) Evaluate the ability of models to capture reconstructed variability on multi-decadal and longer timescales. (b) Determine what fraction of the variability is attributable to “external” forcing and what fraction reflects purely internal variability. (c) Provide a longer-term perspective for detection and attribution studies.	Tier 1*
mid-Holocene (<i>midHolocene</i>) 6 ka	(a) Evaluate the model response to known orbital forcing changes and changes in greenhouse gas concentrations against palaeodata that describe major temperature and hydrological changes. (b) Establish relationships between changes in mean state and variability	Tier 1* PMIP4-CMIP6 entry card
Last Glacial Maximum (<i>lgm</i>) 21 ka	(a) Evaluate how the model performs with ice-age boundary conditions against palaeodata. (b) Provide empirical constraints on global climate sensitivity.	Tier 1* PMIP4-CMIP6 entry card
Last Interglacial (<i>lig127k</i>) 127 ka	(a) Evaluate climate model performance during a period of Northern Hemisphere warmth and a sea-level high stand. (b) Establish the impacts of this climate on sea ice and ice sheets.	Tier 1*
mid-Pliocene Warm Period (<i>midPlioceneEoi400</i>) 3.2 Ma	(a) Evaluate the Earth system response to a long-term CO ₂ forcing analogous to that of the modern. (b) Establish the significance of CO ₂ -induced polar amplification for the stability of the ice sheets, sea ice, and sea level.	Tier 1*

* It is not mandatory to perform all Tier 1 experiments to take part in PMIP4-CMIP6, but it is mandatory to run at least one of the PMIP4-CMIP6 entry cards.

(land area is expanded relative to present due to the lower sea level, Fig. 2), and lower atmospheric greenhouse gas concentrations. It is a particularly relevant time period for understanding near-future climate change because the magnitude of the forcing and temperature response from the LGM to present is comparable to that projected from present to the end of the 21st century (Braconnot et al., 2012).

Evaluation of the PMIP3-CMIP5 MH and LGM experiments has demonstrated that climate models simulate changes in the large-scale features that are governed by the energy and water balance reasonably well (Harrison et al., 2014, 2015; Li et al., 2013), including changes in land–sea contrast and high-latitude amplification of temperature changes (Izumi et al., 2013, 2015). These results confirm that the simulated relationships between large-scale patterns of temperature and precipitation change in future projections are credible. However, the PMIP3-CMIP5 simulations of MH and LGM climates show a limited ability to predict reconstructed patterns of climate change overall (Hargreaves et al., 2013; Hargreaves and Annan, 2014; Harrison et al., 2014, 2015). At least in part, this likely arises from persistent problems in simulating regional climates. For example, state-of-the-art models cannot adequately reproduce the northward penetration of the African monsoon in response to the MH orbital forcing (Perez-Sanz et al., 2014; Pausata et al., 2016), which has been noted since PMIP1 (Joussaume et al., 1999).

While this likely reflects inadequate representation of feedbacks, model biases could also contribute to this mismatch (e.g. Zheng and Braconnot, 2013). Systematic benchmarking of the PMIP3-CMIP5 MH and LGM also shows that better performance in palaeoclimate simulations is not consistently related to better performance under modern conditions, stressing that the ability to simulate modern climate regimes and processes does not guarantee that a model will be good at simulating climate changes (Harrison et al., 2015).

For PMIP4-CMIP6, we have modified the experimental design of the *midHolocene* and *lgm* experiments with the aim of obtaining more realistic representations of these climates (Table 2, Otto-Bliesner et al., 2017, for *midHolocene* and Kageyama et al., 2017, for *lgm*). One of these modifications is the inclusion of changes in atmospheric dust loading (Fig. 3), which can have a large effect on regional climate changes. For *midHolocene*, realistic values of the concentration of atmospheric CO₂ and other trace gases will be used (Otto-Bliesner et al., 2017). This makes this experiment more realistic than in PMIP3, where it was designed as a simple test of the effect of changes in insolation forcing. The PMIP3-CMIP5 *lgm* experiments considered a single ice sheet reconstruction (Abe-Ouchi et al., 2015), which was created by merging three ice sheet reconstructions that were then available. Two of those three reconstructions have since been updated, yet uncertainty about the geometry of the ice

Table 2. Summary of the change in boundary conditions with respect to *piControl* (abbreviated as “PI”) for each PMIP4-CMIP6 experiment. Calendar ages are expressed in Common Era (CE) and geological ages are expressed in thousand years (ka) or million years (Ma) before present (BP), with present defined as 1950.

Period	Greenhouse gas concentrations	Astronomical parameters	Ice sheets	Tropospheric aerosols ^a	Land surface ^b	Volcanoes	Solar activity	Reference to be cited
PMIP4-CMIP6 entry cards								
mid-Holocene (<i>midHolocene</i>) 6 ka	6 ka	6 ka	as in PI	modified (if possible)	interactive vegetation OR interactive carbon cycle OR fixed to present day (depending on model complexity)	as in PI	as in PI	Otto-Bliesner et al. (2017)
Last Glacial mum (<i>lgm</i>) 21 ka	21 ka	21 ka	modified (larger)	modified (if possible)	interactive vegetation OR interactive carbon cycle OR fixed to present day (depending on model complexity)	as in PI	as in PI	Kageyama et al. (2017)
Tier 1 PMIP4-CMIP6 experiments								
Last millennium (<i>past1000</i>) 850–1849 CE	time varying (Meinshausen et al., 2018)	time varying (Berger, 1978; Schmidt et al., 2011)	as in PI	as in PI	time varying (land use)	time-varying radiative forcing due to strato-spheric aerosols	time varying	Junglaus et al. (2017)
Last Interglacial (<i>lig127k</i>) 127 ka	127 ka	127 ka	as in PI	modified (if possible)	interactive vegetation OR interactive carbon cycle OR fixed to present day (depending on model complexity)	as in PI	as in PI	Otto-Bliesner et al. (2017)
mid-Pliocene Warm Period (<i>midPlioceneEoi400</i>) 3.2 Ma	CO ₂ : 400 ppm	as in PI	modified (smaller)	as in PI	interactive vegetation OR Modified to mid-Pliocene OR fixed to present day (depending on model complexity)	as in PI	as in PI	Haywood et al. (2016)

^a Only for models without fully interactive dust (see Sect. 3.3). ^b See Sect. 4.1.

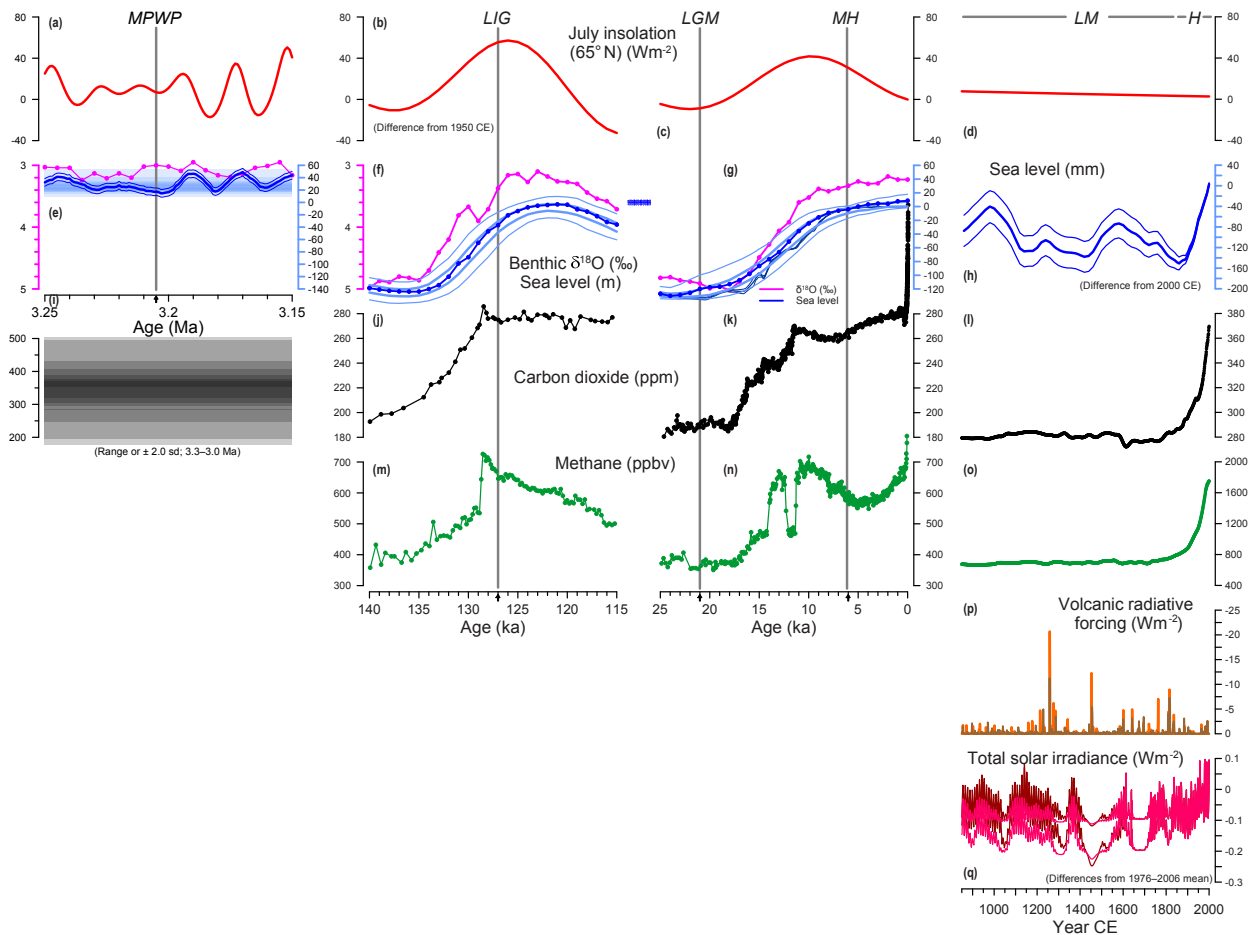


Figure 1. Context of the PMIP4 experiments (from left to right: mPWP, mid-Pliocene Warm Period; LIG, Last Interglacial; LGM, Last Glacial Maximum; MH, mid-Holocene; LM, last millennium; H, CMIP6 historical simulation): (a–d) insolation anomalies (differences from 1950 CE), for July at 65°N, calculated using the programs of Laskar et al. (2004, panel a) and Berger (1978, panels b–d); (e) $\delta^{18}\text{O}$ (magenta, Lisiecki and Raymo, 2005, scale on the left), and sea level (blue line, Rohling et al., 2014; blue shading, a density plot of 11 mid-Pliocene sea-level estimates from Dowsett and Cronin, 1990; Wardlaw and Quinn, 1991; Krantz, 1991; Raymo et al., 2009; Dwyer and Chandler, 2009; Naish and Wilson, 2009; Masson-Delmotte et al., 2013; Rohling et al., 2014; Dowsett et al., 2016. Scale on the right); (f) and (g) $\delta^{18}\text{O}$ (magenta, Lisiecki and Raymo, 2005, $\delta^{18}\text{O}$ scale on the left), and sea level (blue dots, with light-blue 2.5, 25, 75, and 97.5 percentile bootstrap confidence intervals, Spratt and Lisiecki, 2016; blue rectangle, LIG high-stand range, Dutton et al., 2015; dark blue lines, Lambeck et al., 2014, sea-level scale on the right in panel g), (h) sea level (Kopp, et al., 2016, scale on the right); (i) CO_2 for the interval 3.0–3.3 Ma shown as a density plot of eight mid-Pliocene estimates (Raymo et al., 1996; Stap et al., 2016; Pagani et al., 2010; Seki et al., 2010; Tripathi et al., 2009; Bartoli et al., 2011; Seki et al., 2010; Kurschner et al., 1996); (j, k) CO_2 measurements (Bereiter et al., 2015, scale on the left); (l) CO_2 measurements (Schmidt et al., 2011, scale on the right); (m, n) CH_4 measurements (Louergue et al., 2008, scale on the left); (o) CH_4 measurements (Schmidt et al., 2011, scale on the right); (p) volcanic radiative forcing (Schmidt et al., 2012, scale on the right); (q) total solar irradiance (Schmidt et al., 2012, scale on the right).

sheets at the Last Glacial Maximum remains. The protocol for the PMIP4-CMIP6 *lgm* simulations accounts for this uncertainty by permitting modellers to choose between the old PMIP3 ice sheet (Abe-Ouchi et al., 2015) or one of the two new reconstructions: ICE-6G_C (Argus et al., 2014; Peltier et al., 2015) and GLAC-1D (Tarasov et al., 2012; Briggs et al., 2014; Ivanovic et al., 2016). The impact of the ice sheet and dust forcings will specifically be tested in the *lgm* experiments by (i) using different ice sheet reconstructions for

Tier 1 simulations (Fig. 2), (ii) performing *Tier 2* dust sensitivity experiments (Sect. 3.2.1, Kageyama et al., 2017), and (iii) performing *Tier 2* individual forcing sensitivity experiments (Sect. 3.2.2, Kageyama et al., 2017). The inclusion of dust forcing in these simulations is new for PMIP4.

2.2 The last millennium (*past1000*)

The millennium prior to the industrial era, 850–1849 CE, provides a well-documented (e.g. PAGES2k-PMIP3 group,

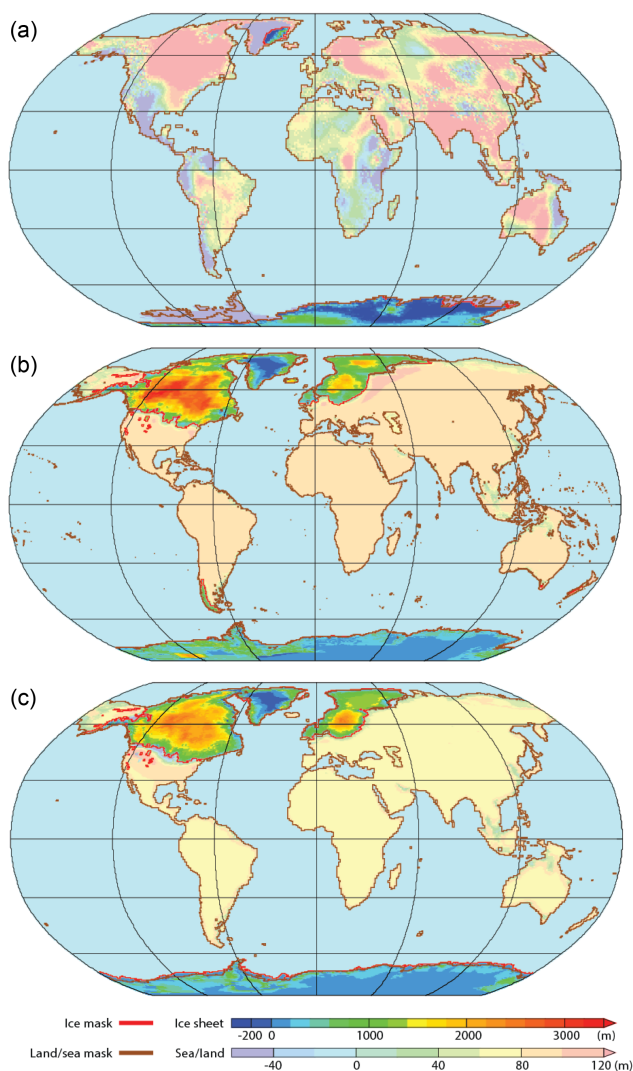


Figure 2. Changes in boundary conditions related to changes in ice sheets for the *midPliocene-eoi400* (a) and *Igm* (b: ICE-6G_C and c: GLAC-1D) experiments. Coastlines for the palaeo-period shown as brown contours. Ice sheet boundaries for each period shown as red contours. Bright shading: changes in altitude over regions covered by ice sheets during the considered palaeo-period. Faded shading: changes in altitude over ice-free regions.

2015) period of multi-decadal to multi-centennial changes in climate, with contrasting periods such as the Medieval Climate Anomaly and the Little Ice Age. This interval was characterized by variations in solar, volcanic, and orbital forcings (Fig. 1), which acted under climatic background conditions similar to today. This interval provides a context for analysing earlier anthropogenic impacts (e.g. land-use changes) and the current warming due to increased atmospheric greenhouse gas concentrations. It also helps constrain the uncertainty in the future climate response to a sustained anthropogenic forcing.

The PMIP3-CMIP5 *past1000* simulations show relatively good agreement with regional climate reconstructions for the Northern Hemisphere, but less agreement for the Southern Hemisphere. They also provided an assessment of climate variability on decadal and longer scales and information on predictability under forced and unforced condition experiments (Fernández-Donado et al., 2013). Single-model ensembles have provided improved understanding of the importance of internal versus forced variability and of the individual forcings when compared to reconstructions at both global and regional scales (Man et al., 2012, 2014; Phipps et al., 2013; Schurer et al., 2014; Man and Zhou, 2014; Otto-Bliesner et al., 2016). Other studies focused on the temperature difference between the warmest and coldest centennial or multi-centennial periods and their relationship with changes in external forcing, in particular variations in solar irradiance (e.g. Hind and Moberg, 2013).

The PMIP4-CMIP6 *past1000* simulation (Jungclaus et al., 2017) builds on the DECK experiments, in particular the pre-industrial control (*piControl*) simulation as an unforced reference, and the *historical* simulations (Eyring et al., 2016). The *past1000* simulations provide initial conditions for *historical* simulations that can be considered superior to the *piControl* state, as they integrate information from the forcing history (e.g. large volcanic eruptions in the early 19th century). It is therefore mandatory to continue the *past1000* simulations into the historical period when running this simulation. The PMIP4-CMIP6 *past1000* protocol uses a new, more comprehensive reconstruction of volcanic forcing (Sigl et al., 2015) and ensures a more continuous transition from the pre-industrial past to the future. The final decisions resulted from strong interactions with the groups producing the different forcing fields for the historical simulations (Jungclaus et al., 2017).

2.3 The Last Interglacial (*lig127k*)

The Last Interglacial (ca. 130–115 ka before present) was characterized by a Northern Hemisphere insolation seasonal cycle that was even larger than for the mid-Holocene (Otto-Bliesner et al., 2017). This resulted in a strong amplification of high-latitude temperatures and reduced Arctic sea ice. Global mean sea level was at least 5 m higher than now for at least several thousand years (e.g. Dutton et al., 2015). Both the Greenland and Antarctic ice sheets contributed to this sea-level rise, making it an important period for testing our knowledge of climate–ice sheet interactions in warm climates. The availability of quantitative climate reconstructions for the Last Interglacial (e.g. Capron et al., 2014) makes it feasible to evaluate these simulations and assess regional climate changes.

Climate model simulations of the Last Interglacial, reviewed in the IPCC AR5 (Masson-Delmotte et al., 2013), varied in their forcings and were not necessarily made with the same model as the CMIP5 future projections. There are

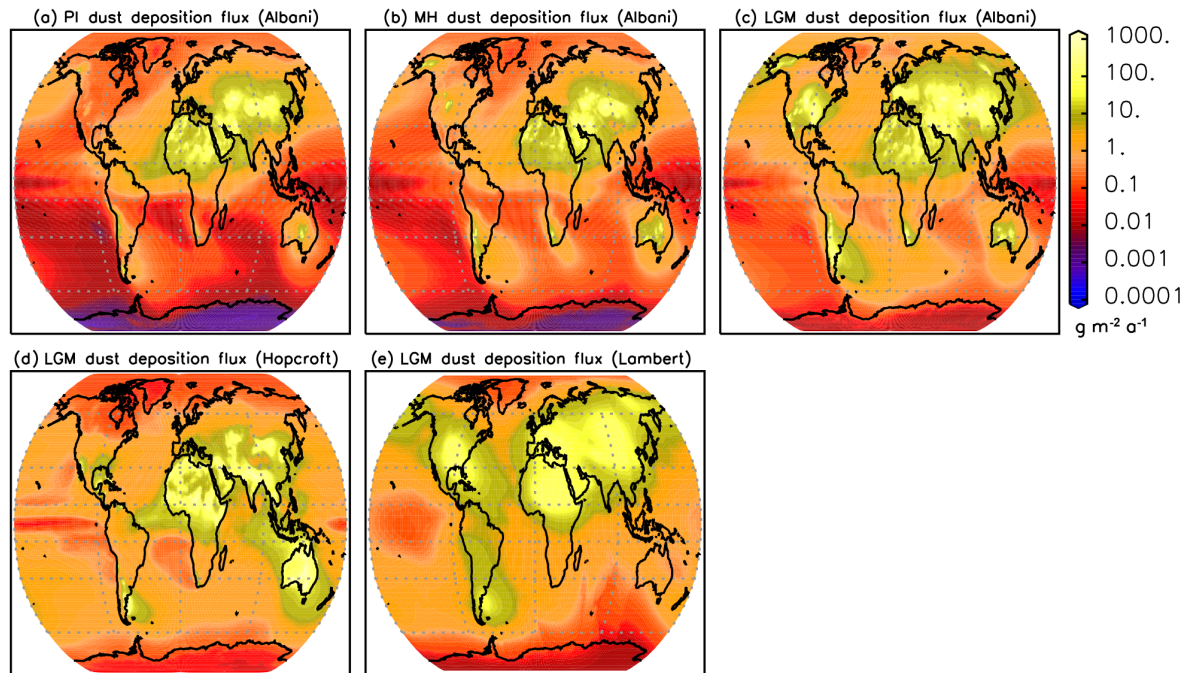


Figure 3. Maps of dust deposition ($\text{g m}^{-2} \text{a}^{-1}$) simulated with the Community Earth System Model for the (a) PI (pre-industrial; Albani et al., 2016), (b) MH (mid-Holocene; Albani et al., 2015), and (c) LGM (Last Glacial Maximum; Albani et al., 2014). Maps of dust deposition ($\text{g m}^{-2} \text{a}^{-1}$) for the LGM, (d) simulated with the Hadley Centre Global Environment Model 2-Atmosphere (Hopcroft et al., 2015), and reconstructed from a global interpolation of palaeodust data (Lambert et al., 2015).

large differences between simulated and reconstructed mean annual surface temperature anomalies compared to present, particularly for Greenland and the Southern Ocean, and in the temperature trends in transient experiments run for the whole interglacial (Bakker et al., 2013; Lunt et al., 2013). Part of this discrepancy stems from the fact that the climate reconstructions comprised the local maximum interglacial warming, and this was not globally synchronous, an issue which is addressed in the PMIP4-CMIP6 protocol.

The PMIP4-CMIP6 *lig127k* experiment will help to determine the interactions between a warmer climate (higher atmospheric and oceanic temperatures, changed precipitation, and changed surface mass and energy balance) and the ice sheets (specifically, their thermodynamics and dynamics). The major changes in the experimental protocol for *lig127k*, compared to the pre-industrial DECK experiment, are changes in the astronomical parameters and greenhouse gas concentrations (Table 2 and Otto-Bliesner et al., 2017). Meaningful analyses of these simulations are now possible because of the concerted effort to synchronize the chronologies of individual records and thus provide a spatial-temporal picture of Last Interglacial temperature change (Capron et al., 2014, 2017), and also to document the timing of the Greenland and Antarctic contributions to sea level (Winsor et al., 2012; Steig et al., 2015). Regional responses of tropical hydroclimate and polar sea ice to the climate forcing can be assessed and compared to the

mid-Holocene. Outputs from the *lig127k* experiment will be used by ISMIP6 to force stand-alone ice sheet experiments (*lastInterglacialforcedism*) in order to quantify the potential sea-level change associated with this climate.

2.4 The mid-Pliocene Warm Period (*midPliocene-eoi400*)

The *midPliocene-eoi400* experiment focuses on the last time in Earth's history when atmospheric CO_2 concentrations approached current values (~ 400 ppmv) with a continental configuration similar to today (Table 2, Figs. 1, 2). Vegetation reconstructions indicate that there was less desert, and boreal forests were present in high northern latitude regions that are covered by tundra today (Salzmann et al., 2008). Climate model simulations from PlioMIP (concomitant with PMIP3) produced global mean surface air temperature anomalies ranging from $+1.9$ to $+3.6^\circ\text{C}$ (relative to each model's pre-industrial control) and an enhanced hydrological cycle (Haywood et al., 2013) with strengthened monsoons (Zhang et al., 2013). These simulations also show that meridional temperature gradients were reduced (due to high-latitude warming), which has significant implications for the stability of polar ice sheets and sea level in the future (e.g. Miller et al., 2012). Model-data comparisons provide high confidence that mean surface temperature was warmer than pre-industrial temperature (Dowsett et al., 2012; Haywood et

al., 2013; Masson-Delmotte et al., 2013). However, as is the case for the Last Interglacial, the PlioMIP simulations were not always performed using the same models that were used in PMIP3-CMIP5.

The PMIP4-CMIP6 *midPliocene-eoi400* experiment (Haywood et al., 2016) is designed to elucidate the long-term response of the climate system to a concentration of atmospheric CO₂ close to the present one: 400 ppm (long-term climate sensitivity or Earth system sensitivity). It will also be used to assess the response of ocean circulation, Arctic sea ice, modes of climate variability (e.g. El Niño–Southern Oscillation), the global hydrological cycle, and regional monsoon systems to elevated concentrations of atmospheric CO₂. The simulations have the potential to be informative about which emission reduction scenarios are required to keep the increase in global annual mean temperatures below 2 °C by 2100 CE. Boundary conditions (Table 2) include modifications to global ice distributions (Fig. 2), topography/bathymetry, vegetation, and CO₂ and are provided by the US Geological Survey Pliocene Research and Synoptic Mapping Project (PRISM4; Dowsett et al., 2016).

2.5 Palaeoclimatic and palaeoenvironmental data for the PMIP4-CMIP6 periods

The choice of the time periods for the PMIP4-CMIP6 simulations has been made bearing in mind the availability of palaeoenvironmental and/or palaeoclimate reconstructions that can be used for model evaluation and diagnosis. Past environmental and climatic changes are typically documented at specific sites, whether on land, in ocean sediments or in corals, or from ice cores. The evaluation of climate simulations such as those conducted for PMIP4-CMIP6 requires these palaeoclimatic and palaeoenvironmental data to be synthesized for specific time periods. A major challenge in building such syntheses is to synchronize the chronologies of the different records. There are many syntheses of information on past climates and environments. Table 3 lists some of the sources of quantitative reconstructions for the PMIP4-CMIP6 time periods, but it is not our goal to provide an extensive review of these resources here.

Much of the information on palaeoclimates comes from the impact of climatic changes on the environment, such as on fires, dust, marine microfauna, and vegetation. Past climatic information is also contained in isotopic ratios of oxygen and carbon, which can be found in ice sheets, speleothems, or the shells of marine organisms. Ocean circulation can be documented by geochemical tracers in marine sediments from the sea floor (e.g. $\Delta^{14}\text{C}$, $\delta^{13}\text{C}$, $^{231}\text{Pa} / ^{230}\text{Th}$, ε_{Nd}). The fact that these physical, chemical, or biological indicators are indirect records of the state of the climate system and can also be sensitive to other factors (for example, vegetation is affected by atmospheric CO₂ concentrations) has to be taken into account in model–data comparisons. Compar-

isons with climate model output can therefore be performed from different points of view: either the climate model output can be directly compared to reconstructions of past climate variables or the response of the climatic indicator itself can be simulated from climate model output and compared to the climate indicator. Such “forward” models include dynamical vegetation models, tree ring models, or models computing the growth of foraminifera, for which specific output is needed (cf. Sect. 4.3). Some palaeoclimatic indicators, such as meteoric water isotopes and vegetation, are computed by the climate model as it is running and are also examples of this forward modelling approach. Modelling the impacts of past climate changes on the environment is key to understanding how climatic signals are transmitted to past climate records. It also provides an opportunity to test the types of models that are used in the assessment of the impacts of future climate changes on the environment.

3 Analysing the PMIP4-CMIP6 experiments

The community using PMIP simulations is very broad, from climate modellers and palaeoclimatologists to biologists studying recent changes in biodiversity and archaeologists studying potential impacts of past climate changes on human populations. Here, we highlight several topics of analyses that will benefit from the new experimental design and from using the full PMIP4-CMIP6 ensemble.

3.1 Comparisons with palaeoclimate and palaeoenvironmental reconstructions, benchmarking, and beyond

Model–data comparisons for each period will be one of the first tasks conducted after completion of these simulations. One new feature common to all periods is that we will make use of the fact that modelling groups must also run the *historical* experiment, in addition to the *piControl* one. Indeed, existing palaeoclimate reconstructions have used different modern reference states (e.g. climatologies for different time intervals) for their calibration, and this has been shown to have an impact on the magnitude of changes reconstructed from climate indicators (e.g. Hessler et al., 2014). These reconstructed climatic changes were usually compared to simulated climate anomalies w.r.t. a *piControl* simulation because running the *historical* simulations was not systematic in previous phases of PMIP. This prevented investigation of the impact of these reference state assumptions on model–data comparisons. More precisely, understanding the impact of the reference states is important for quantifying the uncertainties in interpretations of climate proxies and hence for evaluating model results.

The PMIP4-CMIP6 simulations make a unique contribution to CMIP6 because they enable us to evaluate model performance for different climates against palaeoclimatic re-

constructions, and thus identify possible model biases or other problems (e.g. Hopcroft and Valdes, 2015a). An ensemble of metrics has already been developed for the PMIP3-CMIP5 *midHolocene* and *lgm* simulations (e.g. Harrison et al., 2014). Applied to the PMIP4-CMIP6 *midHolocene* and *lgm* “entry card” simulations, these will provide a rigorous assessment of model improvements compared to previous phases of PMIP. Furthermore, for the first time, thanks to the design of the PMIP4-CMIP6 experiments, we will be able to consider the impact of forcing uncertainties on simulated climate in the benchmarking. The benchmarking metrics will also be expanded to other periods and data sets so that systematic biases for different periods and for the present day can be compared. Benchmarking the ensemble of the PMIP4-CMIP6 simulations for all the periods will therefore allow quantification of the climate-state dependence of the model biases, a topic which is highly relevant for a better assessment of potential biases in the projected climates in CMIP6.

In addition, it will be possible to analyse the potential relationships between model biases in different regions and/or in different variables (such as temperature vs. hydrological cycle) across the PMIP ensemble, as well as for the recent climate. One further objective for the PMIP4-CMIP6 benchmarking will be to develop more process-oriented metrics, making use of the fact that palaeoclimatic data document different aspects of climate change. There are many aspects of the climate system that are difficult to measure directly, and which are therefore difficult to evaluate using traditional methods. The “emergent constraint” (e.g. Sherwood et al., 2014) concept, which is based on identifying a relationship with a more easily measurable variable, has been successfully used by the carbon-cycle and modern climate communities and holds great potential for the analysis of palaeoclimate simulations. Using multiple time periods to examine “emergent” constraints will ensure that they are robust across climate states.

3.2 Analysing the response of the climate system to multiple forcings

Multi-period analyses provide a way of determining whether systematic model biases affect the overall response and the strength of feedbacks independently of climate state. One challenge will be to develop new approaches to analyse the PMIP4-CMIP6 ensemble so as to separate the impacts of model structure (including choice of resolution, parameterizations, and complexity) on the simulated climate. Similarly, the uncertainties in boundary conditions will be addressed for periods with proposed alternative forcings.

Quantifying the role of forcings and feedbacks in creating climates different from today has been a focus of PMIP for many years. Many CMIP6 models will include representations of new forcings, such as dust, or improved representations of major radiative feedback processes, such as those related to clouds. This will allow a broader analysis of feed-

backs than was possible in PMIP3-CMIP5. We will evaluate the impact of these new processes and improved realizations of key forcings on climates at global, large (e.g. polar amplification, land–sea contrast), as well as regional scales, together with the mechanisms explaining these impacts. A particular emphasis will be put on the modulation of the climate response to a given forcing by the background climate state and how it affects changes in cloud feedbacks, snow and ice sheets (such as in e.g. Yoshimori et al., 2011), vegetation, and ocean deep water formation. Identification of similarities between past climates and future climate projections such as that found for land–sea contrast or polar amplification (Izumi et al., 2013, 2015; Masson-Delmotte et al., 2006), or for snow and cloud feedbacks for particular seasons (Braconnot and Kageyama, 2015), will be used to provide better understanding of the relationships between patterns and timescales of external forcings and patterns and timing of the climate responses.

These analyses should provide new constraints on climate sensitivity. Previous attempts that used information about the LGM period have been hampered by the fact that there were too few *lgm* experiments to draw statistically robust conclusions (Crucifix et al., 2006; Hargreaves et al., 2012; Harrison et al., 2014; Hopcroft and Valdes, 2015b). These attempts also ignored uncertainties in forcings and boundary conditions. PMIP4-CMIP6 is expected to result in a much larger ensemble of *lgm* experiments. The issue of climate sensitivity and Earth system sensitivity (PALEOSENS Project Members, 2012) will also be examined through joint analysis of multiple palaeoclimate simulations and climate reconstructions from different archives.

The PMIP4-CMIP6 ensemble will allow new analyses of the impact of smaller (mPWP) or larger (LGM) ice sheets. The ocean and sea ice feedbacks will also be analysed. The representation of sea ice and Southern Ocean circulation proved to be problematic in previous simulations of colder (LGM, Roche et al., 2012) and warmer climates (LIG, Bakker et al., 2013; Lunt et al., 2013) and we are eager to analyse improved models for this area which is key for atmosphere–ocean carbon exchanges. For the LGM, there is evidence of a shallower and yet active overturning circulation in the North Atlantic (e.g. Lynch-Stieglitz et al., 2007; Böhm et al., 2015). Understanding this oceanic circulation for the LGM and the other PMIP4 periods, as well as its links to surface climate, is a topic of high importance since the Atlantic Meridional Overturning Circulation could modulate future climate changes at least in regions around the North Atlantic. The PMIP4 multi-period ensemble, for which we require improved simulations in terms of spin-up, will strengthen the analyses for this particular topic compared to previous phases of PMIP (Marzocchi and Jansen, 2017).

Multi-period analyses will also be useful for understanding the relationship between mean climate state and modes of natural variability (e.g. Liu et al., 2014; Saint-Lu et al., 2015). Analyses of multiple long simulations with different

forcings should provide a better understanding of changes in ENSO behaviour (Zheng et al., 2008; An and Choi, 2014) and help determine whether state-of-the-art climate models underestimate low-frequency variability (Laepple and Huybers, 2014). Analyses will focus on how models reproduce the relationship between changes in seasonality and interannual variability (Emile-Geay et al., 2016), the diversity of El Niño events (Capotondi et al., 2015; Karamperidou et al., 2015; Luan et al., 2015), and the stability of teleconnections within the climate system (e.g. Gallant et al., 2013; Batehup et al., 2015).

3.3 Interactions with other CMIP6 MIPs and the WCRP Grand Challenges

PMIP has already developed strong links with several other CMIP6 MIPs (Table 4). CFMIP includes an idealized experiment that allows the investigation of cloud feedbacks and associated circulation changes in a colder versus warmer world. This will assist in disentangling the processes at work in the PMIP4 simulations. We have also required CFMIP-specific output to be implemented in the PMIP4-CMIP6 simulations so that the same analyses can be carried out for both the PMIP4 and CFMIP simulations. This will ensure that the simulated cloud feedbacks in different past and future climates can be directly compared.

Interactions between PMIP and other CMIP6 MIPs have mutual benefits: PMIP provides (i) simulations of large climate changes that have occurred in the past and (ii) evaluation tools that capitalize on extensive data syntheses, while other MIPs will employ diagnostics and analyses that will be useful for analysing the PMIP4 experiments. We are eager to settle collaborations with the CMIP6 MIPs listed in Table 4 and have ensured that all the outputs necessary for the application of common diagnostics between PMIP and these MIPs will be available (see Sect. 4.3). Links with CFMIP and ISMIP6 mean that PMIP will contribute to the World Climate Research Programme (WCRP) Grand Challenges on “Clouds, Circulation and Climate Sensitivity” and “Cryosphere and Sea Level” respectively. PMIP will provide input to the WCRP Grand Challenge on “Regional Climate Information”, through a focus on evaluating the mechanisms of regional climate change in the past.

4 Model configuration, experimental set-up, documentation, and required output.

To achieve the PMIP4 goals and benefit from other simulations in CMIP6, particular care must be taken with model versions and the implementation of the experimental protocols. Here we summarize the guidelines that are common to all the experiments, focusing on the requirements to ensure strict consistency between CMIP6 and PMIP4 experiments. These concern model complexity, forcings, and mineral dust,

which is a new feature in the PMIP4 experiments. This section also provides guidelines for the documentation and required output. The reader is referred to the PMIP4 companion papers on the specific periods for details of the set-up of each PMIP4-CMIP6 experiment.

4.1 Model version, set-up, and common design of all PMIP4-CMIP6 experiments

The climate models taking part in CMIP6 are very diverse: some represent solely the physics of the climate system, some include the carbon cycle and other biogeochemical cycles, and some include interactive natural vegetation and/or interactive dust cycle/aerosols. It is mandatory that the model version used for the PMIP4-CMIP6 experiments is exactly the same as for the DECK and *historical* simulations. It is highly preferable that it is also exactly the same as for any other CMIP6 experiments, for ease and robustness of comparison between the MIPs. The experimental set-up for each simulation is based on the DECK pre-industrial control (*piControl*) experiment (Eyring et al., 2016), i.e. the *piControl* forcings and boundary conditions are modified to obtain the forcings and boundary conditions necessary for each PMIP4-CMIP6 palaeoclimate experiment (Table 2). No additional interactive component should be included in the model unless it is already included in the DECK version. Such changes would prevent rigorous analyses of the responses to forcings across multiple time periods or between MIPs (Sect. 3) because the differences between the experiments could then arise from both the models’ characteristics and the response to changes in external forcings. Adding an interactive component usually affects the *piControl* simulation as well as simulations of past climates (Braconnot et al., 2007), so it is very important that experiments for PMIP4-CMIP6 and DECK are run with exactly the same model version.

Because of this, even though environmental records show that natural vegetation patterns during each of the PMIP4-CMIP6 periods were different from today, the PMIP4-CMIP6 palaeoclimate simulations should use the same model configuration as the DECK and historical simulations. If the DECK and *historical* simulations use dynamic vegetation, then the PMIP4-CMIP6 palaeoclimate simulations should do so too. If the DECK and *historical* simulations use prescribed vegetation, then the same vegetation should be prescribed in the PMIP4-CMIP6 palaeoclimate simulations. One exception to this is the *midPliocene-eoi400* experiment, where models that prescribe vegetation in the DECK and historical simulations should prescribe the mid-Pliocene vegetation (Haywood et al., 2016). The other exception is for models including an interactive dust cycle for the LGM, which should impose vegetation that allows dust emissions over LGM dust emission regions. Sensitivity experiments to prescribed vegetation are encouraged for each period, as is described in the companion papers.

Table 3. Examples of data syntheses for the PMIP4-CMIP6 periods. MAT: mean annual temperature; MAP: mean annual precipitation; α : ratio of the actual evaporation over potential evaporation; MTCO: mean temperature of the coldest month; MTWA: mean temperature of the warmest month; SST: sea-surface temperature.

Reference	Variables	Time period	Comments	Data available from
Mann et al. (2009)	MAT	500–2006 CE	Gridded data set (5°)	http://science.sciencemag.org/content/suppl/2009/11/25/326.5957.1256.DC1
PAGES 2k Consortium (2013)	MAT	past 2000 years	Individual sites; Arctic data updated 2014	https://www.ncdc.noaa.gov/paleo-search/study/12621
Bartlein et al. (2011)	MAT, MAP, α , MTCO, MTWA	6000 \pm 500 yr; 21 000 \pm 1000 yr	Gridded data set (2°)	https://www.ncdc.noaa.gov/paleo/study/9897
MARGO Project Members (2009)	Mean annual, winter, summer SST	21000 \pm 2000 yr	Gridded data set (5°)	http://www.ncdc.noaa.gov/paleo/study/12034 http://doi.pangaea.de/10.1594/PANGAEA.733406
Turney and Jones (2010)	MAT, SST	Maximum warmth during LIG	Individual sites (100 terrestrial; 162 marine)	http://onlinelibrary.wiley.com/store/10.1002/jqs.1423/asset/supinfo/JQS_1423_sm_supInfo.pdf?v=1&s=1726938c44b8762e15aaf17514fc076c855b8ed1
Capron et al. (2014, 2017)	MAT, summer SST	114–116, 119–121, 124–126, 126–128, 129–131 ka	47 high-latitude sites	https://doi.org/10.1594/PANGAEA.841672
Dowsett et al. (2012)	SST	3.264–3.025 Ma	Further information available in Dowsett et al. (2016)	http://www.nature.com/nclimate/journal/v2/n5/full/nclimate1455.html#supplementary-information
Salzmann et al. (2013)	MAT	3.3–3.0 Ma		http://www.nature.com/nclimate/journal/v3/n11/extref/nclimate2008-s1.pdf

Two experiments, *lgm* and *midPliocene-eoi400*, require modified ice sheets (Fig. 2), which also implies consistent modification of the coastlines, ocean bathymetry (if feasible for *midPliocene-eoi400*), topography, and land surface types over the continents, and to ensure that rivers reach the ocean in order to close the global freshwater budget. The initial global mean ocean salinity should be adjusted for these ice volume changes and modelling groups are advised to ensure that the total mass of the atmosphere remains the same in all experiments.

For each experiment, the greenhouse gases and astronomical parameters should be modified from the DECK *piControl* experiment (Table 2). Spin-up procedures will differ according to the model and type of simulation, but the spin-up should be long enough to avoid significant drift in the analysed data. Initial conditions for the spin-up can be taken from an existing simulation. The model should be run until the absolute value of the trend in global mean sea-surface temperature is less than 0.05 K per century and the Atlantic Meridional Overturning Circulation is stable. A parallel requirement for carbon-cycle models and/or models with dynamic

vegetation is that the 100-year mean global carbon uptake or release by the biosphere is $< 0.01 \text{ Pg C yr}^{-1}$.

4.2 A new feature of the PMIP simulations: mineral dust

Natural aerosols show large variations on glacial–interglacial timescales, with glacial climates having higher dust loadings than interglacial climates (Kohfeld and Harrison, 2001; Maher et al., 2010). Dust emissions from northern Africa were significantly reduced during the MH (McGee et al., 2013). As is the case with vegetation, the treatment of dust in the *midHolocene*, *lig127k*, and *lgm* simulations should parallel the treatment in the *piControl*. However, for models with interactive dust schemes, maps of soil erodibility that account for changes in the extension of possible dust sources are provided for the *midHolocene*, *lig127k*, and *lgm* experiments. Dust anomalies/ratios compared to the pre-industrial background should be used for consistency with the DECK *piControl* simulation. As there have been instances of runaway climate–vegetation–dust feedback, leading to unrealistically cold LGM climates (Hopcroft and Valdes, 2015a), it is advis-

Table 4. Interactions of PMIP and other CMIP6 MIPs.

MIP abbreviation and reference	MIP full name	Themes of interactions
CF-MIP (Webb et al., 2017)	Cloud Feedback Model Inter-comparison Project	Dedicated common idealized sensitivity experiment to be run in aquaplanet set-up, <i>AMIPminus4K</i> , to be co-analysed in CF-MIP and PMIP.
ISMIP6 (Nowicki et al., 2016)	Ice Sheet Model Intercomparison Project for CMIP6	Assessment of the climate and cryosphere interactions and the sea-level changes associated with large ice sheets. In particular, the <i>lig127k</i> simulation will be used to force ice sheet models in ISMIP6. Additional experiments co-designed by the PMIP and ISMIP groups are foreseen outside the CMIP6 exercise: transient interglacial experiments, with climate model output forcing an ice sheet model, and coupled climate–ice sheet experiments.
OMIP (Griffies et al., 2016)	Ocean Model Intercomparison Project	Mutual assessment of the role of the ocean in low-frequency variability, e.g. multi-decadal changes in ocean heat content or heat transport. Provide initial conditions for the ocean, including long-term forcing history.
SIMIP (Notz et al., 2016)	Sea Ice Model Intercomparison Project	Assessment of the role of sea ice in climate changes.
AerChemMIP (Collins et al., 2017)	Aerosols and Chemistry Model Intercomparison Project	Assessment of the role of aerosols in climate changes (very helpful since this is a new aspect in PMIP experiments for the mid-Holocene, Last Interglacial, and LGM).
LS3MIP (van den Hurk et al., 2016)	Land Surface, Snow and Soil Moisture Model Intercomparison Project	Assessment of the role of land surface processes in climate changes.
C4MIP (Jones et al., 2016)	Coupled Climate Carbon Cycle Model Intercomparison Project	Assessment of carbon-cycle evolution and feedbacks between sub-components of the Earth system. Evaluation of palaeo-reconstructions of carbon storage.
LUMIP (Lawrence et al., 2016)	Land-Use Model Intercomparison Project	Analysis of climate changes associated with land-use changes (<i>past1000</i> experiment)
VolMIP (Zanchettin et al., 2016)	Volcanic Forcings Model Intercomparison Project	Analysis of specific volcanic events (very useful for critical analysis of <i>past1000</i> simulations). VolMIP will systematically assess uncertainties in the climate response to volcanic forcing, whereas <i>past1000</i> simulations describe the climate response to volcanic forcing in long transient simulations where related uncertainties are caused by chosen input data for volcanic forcing: mutual assessment of forced response.
DAMIP (Gillett et al., 2016)	Detection and Attribution Model Intercomparison Project	<i>past1000</i> simulations provide a long-term reference background, including natural climate variability for detection and attribution.
RFMIP (Pincus et al., 2016)	Radiative Forcing Model Intercomparison Project	Compare radiative forcing from LGM GHG as computed by climate models and by offline fine-scale radiative transfer codes.

able to test the atmosphere model behaviour before running the fully coupled *lgm* simulation.

To allow experiments with prescribed dust changes, three-dimensional monthly climatologies of dust atmospheric mass concentrations are provided for the *piControl*, *midHolocene*, and *lgm*. These are based on two different models (Albani et al., 2014, 2015, 2016; Hopcroft et al., 2015, Fig. 3) and modelling groups are free to choose between these data sets. Additional dust-related fields (dust emission flux, dust load, dust aerosol optical thickness, short- and long-wave radiation, surface and top of the atmosphere dust radiative forcing) are also available from these simulations. Implementation should follow the same procedure as for the *historical* experiment. The implementation for the *lig127k* experiment should use the same data set as for the *midHolocene* one. Since dust plays an important role in ocean biogeochemistry (e.g. Kohfeld et al., 2005), three dust maps are provided for the *lgm* experiment. Two of these are consistent with the climatologies of dust atmospheric mass concentrations; the other is primarily derived from palaeoenvironmental observations (Lambert et al., 2015, Fig. 3). The modelling groups should use consistent data sets for the atmosphere and the ocean biogeochemistry. The Lambert et al. (2015) data set can therefore be used for models that cannot include the changes in atmospheric dust according to the other two data sets.

4.3 Documentation and required model output for the PMIP4-CMIP6 database

Detailed documentation of the PMIP4-CMIP6 simulations is required. This should include

- a description of the model and its components;
- information about the boundary conditions used, particularly when alternatives are allowed;
- information on the implementation of boundary conditions and forcings. Figures showing the land–sea mask, land–ice mask, and topography as implemented in a given model are useful for the *lgm* and *midPliocene-eoi400* experiments, while figures showing insolation are particularly important for the *midHolocene* and *lig127k* experiments. Checklists for the implementation of simulations are provided in the PMIP4 papers, which give detailed information for each experiment; and
- information about the initial conditions and spin-up technique used. A measure of the changes in key variables (Table 5) should be provided in order to assess remaining drift.

Documentation should be provided via the ESDOC website and tools provided by CMIP6 (<http://es-doc.org/>) to facilitate communication with other CMIP6 MIPs. This documentation should also be provided for the PMIP4 website to facili-

tate linkages with non-CMIP6 simulations. The PMIP4 special issue, shared between *Geoscientific Model Development* and *Climate of the Past*, provides a further opportunity for modelling groups to document specific aspects of their simulations. We also require the groups to document the spin-up phase of the simulations by saving a limited set of variables during this phase (Table 5).

The data stored in the CMIP6 database should be representative of the equilibrium climates of the MH, LGM, LIG, and mPWP periods, and of the transient evolution of climate between 850 and 1849 CE for the *past1000* simulations. A minimum of 100 years' output is required for the equilibrium simulations but, given the increasing interest in analysing multi-decadal variability (e.g. Wittenberg, 2009), modelling groups are encouraged to provide outputs for 500 years or more if possible. Daily values should also be provided and will allow the calendar issue to be accounted for (see Appendix). The list of variables required to analyse the PMIP4-CMIP6 palaeoclimate experiments (<https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:wg:db:cmip6request>) reflects plans for multi-time period analyses and for interactions with other CMIP6 MIPs. We have included relevant variables from the data requests of other MIPs, including the CFMIP-specific diagnostics on cloud forcing, as well as land surface, snow, ocean, sea ice, aerosol, carbon cycle, and ice sheet variables from LS3MIP, OMIP, SIMIP, AerChemMIP, C4MIP, and IS-MIP6 respectively. Some of these variables are also required to diagnose how climate signals are recorded by palaeoclimatic sensors via models of tree growth (Li et al., 2014), vegetation dynamics (Prentice et al., 2011), or marine planktonic foraminifera (e.g. Lombard et al., 2011; Kageyama et al., 2013), for example. The only set of variables defined specifically for PMIP are those describing oxygen isotopes in the climate system. Isotopes are widely used for palaeoclimatic reconstruction and are explicitly simulated in several models. We have asked that mean annual cycles of key variables are included in the PMIP4-CMIP6 data request for equilibrium simulations, as these proved exceptionally useful for analyses in PMIP3-CMIP5.

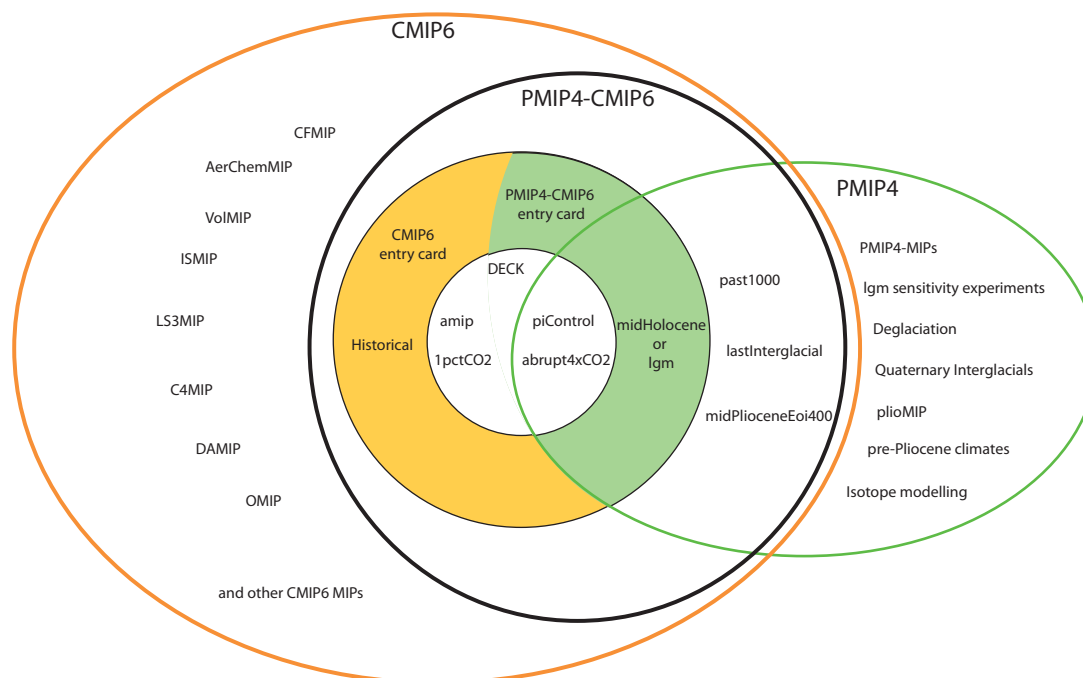
5 Conclusions

The PMIP4-CMIP6 simulations provide a framework to compare current and future anthropogenic climate change with past natural variations of the Earth's climate. PMIP4-CMIP6 is a unique opportunity to simulate past climates with exactly the same models as are used for simulations of the future. This approach is only valid if the model versions and implementation of boundary conditions are consistent for all periods, and if these boundary conditions are seamless for overlapping periods.

PMIP4-CMIP6 simulations are important in terms of model evaluation for climate states significantly different from the present and historical climates. We have chosen

Table 5. Variables to be saved for the documentation of the spin-up phase of the models.

Atmospheric variables	top of atmosphere energy budget (global and annual mean)
	surface energy budget (global and annual mean)
	northern surface air temperature (annual mean over the Northern Hemisphere)
	southern surface air temperature (annual mean over the Southern Hemisphere)
Oceanic variables	Sea-surface temperatures (global and annual mean)
	deep ocean temperatures (global and annual mean over depths below 2500 m)
	deep ocean salinity (global and annual mean over depths below 2500 m)
	Atlantic Meridional Overturning Circulation (maximum overturning strength between 0 and 80° N and below 500 m in depth)
Sea ice variables	northern sea ice (annual mean over the Northern Hemisphere)
	southern sea ice (annual mean over the Southern Hemisphere)
Carbon-cycle variables	Global carbon budget

**Figure 4.** The PMIP4-CMIP6 experiments in the framework of CMIP6 (a), with associated MIPs; and in the framework of PMIP4, with its working groups (b).

climatic periods well documented by palaeoclimatic and palaeoenvironmental records, with climate and environmental changes relevant for the study and projections of future climate changes: the millennium prior to the industrial epoch (*past1000*), 6000 years ago (*midHolocene*), the Last Glacial Maximum (*lgm*), the Last Interglacial (*lig127k*), and the mid-Pliocene Warm Period (*midPliocene-eoi400*).

The PMIP4-CMIP6 experiments will also constitute reference simulations for projects developed in the broader PMIP4 initiative. The corresponding sensitivity experiments, or additional experiments, are embedded in the PMIP4 project and are described in the companion papers to this

overview (Haywood et al., 2016; Otto-Bliesner et al., 2017; Jungclaus et al., 2017; Kageyama et al., 2017). They are essential for a deeper understanding of the drivers of past climate changes for the PMIP4-CMIP6 climates or as initial conditions for transient simulations (e.g. Ivanovic et al., 2016, for the last deglaciation; Otto-Bliesner et al., 2017, for the Last Interglacial and the Holocene), or for examining time periods from deeper time with high atmospheric CO₂ concentrations (Lunt et al., 2017). Figure 4 summarizes the position of the PMIP4-CMIP6 experiments with respect to the other PMIP4 initiatives (right-hand side). The left-hand side of Fig. 4 shows how the PMIP4-CMIP6 experiments

relate to the CMIP6 DECK and some other CMIP6 MIPs. PMIP4-CMIP6 experiments have been designed to be analysed by both communities.

The PMIP community anticipates major benefits from analysis techniques developed by the other CMIP6 MIPs, in particular in terms of learning about the processes of past climate changes in response to forcings (e.g. greenhouse gases, astronomical parameters, ice sheet and sea-level changes) as well as the role of feedbacks (e.g. clouds, ocean, sea ice). PMIP4-CMIP6 has the potential to be mutually beneficial for the palaeoclimate and present/future climate scientists to learn about natural large climate changes and the mechanisms at work in the climate system for climate states that are different from today, as future climate is projected to be.

Data availability. All data mentioned in the present paper can be downloaded following the instructions given in the companion PMIP4-CMIP6 protocol papers (Otto-Bliesner et al., 2017; Jungclaus et al., 2017; Kageyama et al., 2017; Haywood et al., 2016).

Appendix A: Justification of the requirement to save high-frequency output (daily and 6-hourly)

Variations in the shape of the Earth's orbit govern the latitudinal and seasonal distribution of insolation, and also produce variations in the lengths of individual "months" (where months are defined alternatively as either (a) the duration in days for the Earth to complete one-twelfth of its orbit, i.e. the "celestial" or "angular" calendar; or (b) a specific number of days, for example 31 days in January, 30 days in June, i.e. the "conventional" or "modern" calendar). For example, at 6 ka, perihelion occurs in August and aphelion occurs in February. Those months were approximately 1.5 days shorter and longer than at present respectively (Fig. A1). The effect of the changing calendar on the calculation of long-term means can be as large as the potential differences among the means themselves (Joussaume and Braconnot, 1997; Pollard and Reusch, 2002; Timm et al., 2008; Chen et al., 2011). Therefore, variations in the lengths of months (or seasons) must be taken into consideration when examining experiment-minus-control long-term mean differences. The size of the potential calendar effect (or "bias") is illustrated in Fig. A1, and is even larger for *lig127k*, when eccentricity was large. This figure shows the difference between present-day long-term means for October temperature and precipitation, and those calculated using the appropriate celestial month lengths for 6 and 127 ka. Modifications to month length have not usually been taken into account in the post-processing procedures for model output (but see Harrison et al., 2014). An approach to deal with the calendar issue is to use bias-correction, such as that of Pollard and Reusch (2002), with the mean-preserving daily interpolation approach of Epstein (1991). For the PMIP4-CMIP6 simulations, we strongly recommend that daily data are provided for the calculation of monthly or seasonal means, and so we include those in the PMIP4-CMIP6 data request for some key variables. Daily or 6-hourly data are also useful for running regional models. It is important to test the use of regional models for climate model projections at the regional scale. Regional models are also used to produce fine-scale palaeoclimate scenarios for use by the impact community, for example, to study past climate impacts on biodiversity via ecological niche modelling. Palaeoclimate indicators often respond to climate features not adequately captured with monthly data alone (such as growing season length). Daily weather variables are therefore required for some forward models, as well as for the computation of bioclimatic variables that are reconstructed from pollen data, for example (e.g. Bartlein et al., 2011).

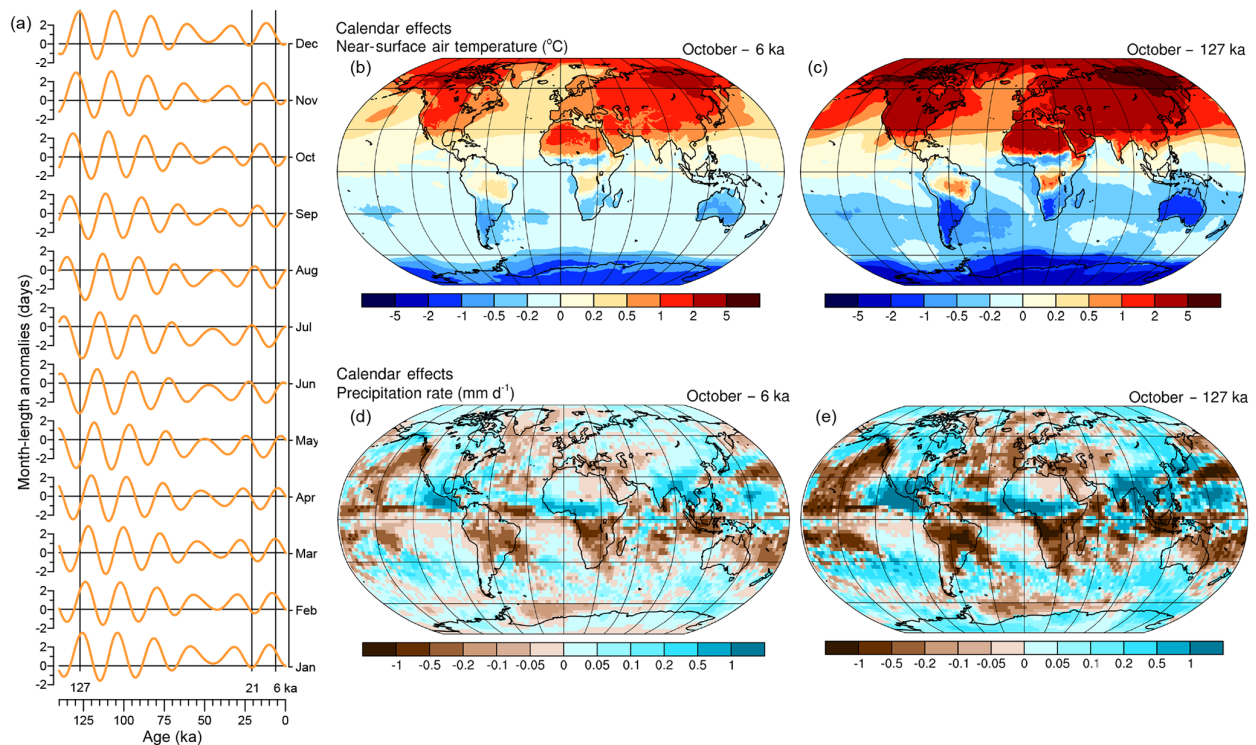


Figure A1. The calendar effect: (a) month-length anomalies, 140 ka to present, with the PMIP4 experiment times indicated by vertical lines. The month-length anomalies were calculated using the formulation in Kutzbach and Gallimore (1988). (b, c) The calendar effect on October temperature at 6 and 127 ka, calculated using Climate Forecast System Reanalysis near-surface air temperature (<https://www.earthsystemcog.org/projects/obs4mips/>), 1981–2010 long-term means, and assuming the long-term mean differences in temperature are zero everywhere. (d, e) The calendar effect on October precipitation at 6 and 127 ka, calculated using the CPC Merged Analysis of Precipitation (CMAP) enhanced precipitation (<http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html>), 1981–2010 long-term means, and again assuming that the long-term mean differences in precipitation are zero everywhere. Calendar effects were calculated by interpolating present-day monthly temperature or precipitation to a daily time step as in Pollard and Reusch (2002, but using a mean-preserving algorithm for pseudo-daily interpolation for monthly values; Epstein, 1991), and then recalculating the monthly means using the appropriate palaeo-calendar (Bartlein and Shafer, 2016). Note that the 6 and 127 ka map patterns for both variables, while broadly similar, are not simply rescaled versions of one another.

Author contributions. MK, PB, and SH organized the main text. The text for each period was initially provided by the leaders of the companion papers, who collated and summarized the contribution of their groups: JJ for the last millennium, BOB for the interglacials, MK for the Last Glacial Maximum, and AH for the mid-Pliocene Warm Period. All authors agreed on the experimental design and contributed text on the background, forcing data sets, or topics in the analysis plan. In addition, the consistency of the forcing data sets for all periods was carefully checked by the contributors of the data sets. The Appendix was written and illustrated by PJB. The final text was refined by RI.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. Masa Kageyama and Qiong Zhang acknowledge funding from French–Swedish project GIWA. Pascale Braconnot, Johann Jungclauss, and Sandy P. Harrison acknowledge funding from JPI-Belmont project “PAleo-Constraints on Monsoon Evolution and Dynamics (PACMEDY)” through their respective national funding agencies. Sandy P. Harrison also acknowledges funding from the Australian Research Council (DP1201100343) and from the European Research Council for “GC2.0: Unlocking the past for a clearer future”. Alan M. Haywood and Aisling Dolan acknowledge funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007–2013)/ERC grant agreement no. 278636 and the EPSRC-supported Past Earth Network. Ruza F. Ivanovic is funded by a NERC Independent Research Fellowship (no. NE/K008536/1). Steven J. Phipps’s contribution is supported under the Australian Research Council’s Special Research Initiative for the Antarctic Gateway Partnership (project ID SR140300001). Fabrice Lambert acknowledges support from CONICYT projects 15110009, 1151427, ACT1410, and NC120066.

Edited by: Julia Hargreaves

Reviewed by: Steven Sherwood and three anonymous referees

References

- Abe-Ouchi, A., Saito, F., Kageyama, M., Braconnot, P., Harrison, S. P., Lambeck, K., Otto-Bliesner, B. L., Peltier, W. R., Tarasov, L., Peterschmitt, J.-Y., and Takahashi, K.: Ice-sheet configuration in the CMIP5/PMIP3 Last Glacial Maximum experiments, *Geosci. Model Dev.*, 8, 3621–3637, <https://doi.org/10.5194/gmd-8-3621-2015>, 2015.
- Albani, S., Mahowald, N. M., Perry, A. T., Scanza, R. A., Zender, C. S., Heavens, N. G., Maggi, V., Kok, J. F., and Otto-Bliesner, B. L.: Improved representation of dust size and optics in the CESM, *J. Adv. Model. Earth Sy.*, 6, 541–570, <https://doi.org/10.1002/2013MS000279>, 2014.
- Albani, S., Mahowald, N. M., Winckler, G., Anderson, R. F., Bradtmiller, L. I., Delmonte, B., François, R., Goman, M., Heavens, N. G., Hesse, P. P., Hovan, S. A., Kang, S. G., Kohfeld, K. E., Lu, H., Maggi, V., Mason, J. A., Mayewski, P. A., McGee, D., Miao, X., Otto-Bliesner, B. L., Perry, A. T., Pourmand, A., Roberts, H. M., Rosenbloom, N., Stevens, T., and Sun, J.: Twelve thousand years of dust: the Holocene global dust cycle constrained by natural archives, *Clim. Past*, 11, 869–903, <https://doi.org/10.5194/cp-11-869-2015>, 2015.
- Albani, S., Mahowald, N. M., Murphy, L. N., Raiswell, R., Moore, J. K., Anderson, R. F., McGee, D., Bradtmiller, L. I., Delmonte, B., Hesse, P. P., and Mayewski, P. A.: Paleodust variability since the Last Glacial Maximum and implications for iron inputs to the ocean, *Geophys. Res. Lett.*, 43, 3944–3954, <https://doi.org/10.1002/2016GL067911>, 2016.
- An, S.-I. and Choi, J.: Mid-Holocene tropical Pacific climate state, annual cycle, and ENSO in PMIP2 and PMIP3, *Clim. Dynam.*, 43, 957–970, <https://doi.org/10.1007/s00382-013-1880-z>, 2014.
- Argus, D. F., Peltier, W. R., Drummond, R., and Moore, A. W.: The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories, *Geophys. J. Int.*, 98, 537–563, <https://doi.org/10.1093/gji/ggu140>, 2014.
- Bakker, P., Stone, E. J., Charbit, S., Gröger, M., Krebs-Kanzow, U., Ritz, S. P., Varma, V., Khon, V., Lunt, D. J., Mikolajewicz, U., Prange, M., Renssen, H., Schneider, B., and Schulz, M.: Last interglacial temperature evolution – a model inter-comparison, *Clim. Past*, 9, 605–619, <https://doi.org/10.5194/cp-9-605-2013>, 2013.
- Bartlein, P. J. and Shafer, S. L.: The impact of the “calendar effect” and pseudo-daily interpolation algorithms on paleoclimatic data-model comparisons, available at: <https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/187186> (last access: 6 March 2018), 2016.
- Bartlein, P. J., Harrison, S. P., Brewer, S., Connor, S., Davis, B. A. S., Gajewski, K., Guiot, J., Harrison-Prentice, T. I., Henderson, A., Peyron, O., Prentice, I. C., Scholze, M., Seppä, H., Shuman, B., Sugita, S., Thompson, R. S., Vial, A., Williams, J., and Wu, H.: Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis, *Clim. Dynam.*, 37, 775–802, 2011.
- Bartoli, G., Honisch, B., and Zeebe, R. E.: Atmospheric CO₂ decline during the Pliocene intensification of Northern Hemisphere glaciations, *Paleoceanography*, 26, PA4213, <https://doi.org/10.1029/2010PA002055>, 2011.
- Batehup, R., McGregor, S., and Gallant, A. J. E.: The influence of non-stationary teleconnections on palaeoclimate reconstructions of ENSO variance using a pseudoproxy framework, *Clim. Past*, 11, 1733–1749, <https://doi.org/10.5194/cp-11-1733-2015>, 2015.
- Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and Chappellaz, J.: Revision of the EPICA Dome C CO₂ record from 800 to 600 kyr before present, *Geophys. Res. Lett.*, 42, 2014GL061957, <https://doi.org/10.1002/2014GL061957>, 2015.
- Berger, A.: Long-term variations of daily insolation and quaternary climatic changes, *J. Atmos. Sci.*, 35, 2362–2367, 1978.
- Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M. B., and Deininger, M.: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle, *Nature*, 517, 73–76, <https://doi.org/10.1038/nature14059>, 2015.
- Braconnot, P. and Kageyama, M.: Shortwave forcing and feedbacks in Last Glacial Maximum and Mid-Holocene PMIP3 simulations, *Phil. T. Roy. Soc. A*, 373, 20140424, <https://doi.org/10.1098/rsta.2014.0424>, 2015.

- Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget, *Clim. Past*, 3, 279–296, <https://doi.org/10.5194/cp-3-279-2007>, 2007.
- Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B., and Zhao, Y.: Evaluation of climate models using palaeoclimatic data, *Nat. Clim. Change*, 2, 417–424, 2012.
- Briggs, R. D., Pollard, D., and Tarasov, L.: A data-constrained large ensemble analysis of Antarctic evolution since the Eemian, *Quaternary Sci. Rev.*, 103, 91–115, <https://doi.org/10.1016/j.quascirev.2014.09.003>, 2014.
- Caballero, R. and Huber, M.: Spontaneous transition to superrotation in warm climates simulated by CAM3, *Geophys. Res. Lett.*, 37, L11701, <https://doi.org/10.1029/2010GL043468>, 2010.
- Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J.-Y., Braconnot, P., Cole, J., Dewitte, B., Giese, B., Guilyardi, E., Jin, F.-F., Karnauskas, K., Kirtman, B., Lee, T., Schneider, N., Xue, Y., and Yeh, S.-W.: Understanding ENSO Diversity, *B. Am. Meteorol. Soc.*, 96, 921–938, <https://doi.org/10.1175/Bams-D-13-00117.1>, 2015.
- Capron, E., Govin, A., Stone, E. J., Masson-Delmotte, V., Mulitza, S., Otto-Bliesner, B., Rasmussen, T. L., Sime, L. C., Waelbroeck, C., and Wolff, E. W.: Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the Last Interglacial, *Quaternary Sci. Rev.*, 103, 116–133, 2014.
- Capron, E., Govin, A., Feng, R., Otto-Bliesner, B., and Wolff, E. W.: Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions, *Quaternary Sci. Rev.*, 168, 137–150, <https://doi.org/10.1016/j.quascirev.2017.04.019>, 2017.
- Chen, G.-S., Kutzbach, J. E., Gallimore, R., and Liu, Z.: Calendar effect on phase study in paleoclimate transient simulation with orbital forcing, *Clim. Dynam.*, 37, 1949–1960, 2011.
- Collins, W. J., Lamarque, J.-F., Schulz, M., Boucher, O., Eyring, V., Hegglin, M. I., Maycock, A., Myhre, G., Prather, M., Shindell, D., and Smith, S. J.: AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6, *Geosci. Model Dev.*, 10, 585–607, <https://doi.org/10.5194/gmd-10-585-2017>, 2017.
- Crucifix, M.: Does the Last Glacial Maximum constrain climate sensitivity?, *Geophys. Res. Lett.*, 33, L18701, <https://doi.org/10.1029/2006GL027137>, 2006.
- Dowsett, H. J. and Cronin, T. M.: High eustatic sea level during the middle Pliocene: Evidence from the southeastern U.S. Atlantic Coastal Plain, *Geology*, 18, 435–438, 1990.
- Dowsett, H. J., Robinson, M. M., Haywood, A. M., Hill, D. J., Dolan, A. M., Stoll, D. K., Chan, W.-L., Abe-Ouchi, A., Chandler, M. A., and Rosenbloom, N. A.: Assessing confidence in Pliocene sea surface temperatures to evaluate predictive models, *Nat. Clim. Change*, 2, 365–371, 2012.
- Dowsett, H., Dolan, A., Rowley, D., Moucha, R., Forte, A. M., Mitrovica, J. X., Pound, M., Salzmann, U., Robinson, M., Chandler, M., Foley, K., and Haywood, A.: The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction, *Clim. Past*, 12, 1519–1538, <https://doi.org/10.5194/cp-12-1519-2016>, 2016.
- Dutton, A., Carlson, A. E., Long, A. J., Milne, G. A., Clark, P. U., DeConto, R., Horton, B. P., Rahmstorf, S., and Raymo, M. E.: Sea-level rise due to polar ice-sheet mass loss during past warm periods, *Science*, 349, aaa4019, <https://doi.org/10.1126/science.aaa4019>, 2015.
- Dwyer, G. S. and Chandler, M. A.: Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes, *Philos. T. Roy. Soc. A*, 367, 157–168, 2009.
- Emile-Geay, J., Cobb, K. M., Carré, M., Braconnot, P., Leloup, J., Zhou, Y., Harrison, S. P., Corrège, T., McGregor, H. V., Collins, M., Driscoll, R., Elliot, M., Schneider, B., and Tudhope, A.: Links between tropical Pacific seasonal, interannual and orbital variability during the Holocene, *Nat. Geosci.*, 9, 168–173, <https://doi.org/10.1038/ngeo2608>, 2016.
- Epstein, E. S.: On obtaining daily climatological values from monthly means, *J. Climate*, 4, 365–368, 1991.
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geosci. Model Dev.*, 9, 1937–1958, <https://doi.org/10.5194/gmd-9-1937-2016>, 2016.
- Fernández-Donado, L., González-Rouco, J. F., Raible, C. C., Ammann, C. M., Barriopedro, D., García-Bustamante, E., Jungclauss, J. H., Lorenz, S. J., Luterbacher, J., Phipps, S. J., Servonnat, J., Swingedouw, D., Tett, S. F. B., Wagner, S., Yiou, P., and Zorita, E.: Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium, *Clim. Past*, 9, 393–421, <https://doi.org/10.5194/cp-9-393-2013>, 2013.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., and Rummukainen, M.: Evaluation of climate models, in: *Climatic Change 2013: The Physical Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
- Gallant, A. J. E., Phipps, S. J., Karoly, D. J., Mullan, A. B., and Lorey, A. M.: Non-stationary Australasian teleconnections and implications for paleoclimate research, *J. Climate*, 26, 8827–8849, <https://doi.org/10.1175/JCLI-D-12-00338.1>, 2013.
- Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6, *Geosci. Model Dev.*, 9, 3685–3697, <https://doi.org/10.5194/gmd-9-3685-2016>, 2016.
- Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Heimbach, P., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclauss, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso,

- M., Wang, Q., Winton, M., and Yeager, S. G.: OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project, *Geosci. Model Dev.*, 9, 3231–3296, <https://doi.org/10.5194/gmd-9-3231-2016>, 2016.
- Hargreaves, J. C. and Annan, J. D.: Can we trust climate models?, invited opinion article for WIREs Climate Change, *WIREs Clim. Change*, 5, 435–440, <https://doi.org/10.1002/wcc.288>, 2014.
- Hargreaves, J. C., Annan, J. D., Yoshimori, M., and Abe-Ouchi, A.: Can the Last Glacial Maximum constrain climate sensitivity?, *Geophys. Res. Lett.*, 39, L24702, <https://doi.org/10.1029/2012GL053872>, 2012.
- Hargreaves, J. C., Annan, J. D., Ohgaito, R., Paul, A., and Abe-Ouchi, A.: Skill and reliability of climate model ensembles at the Last Glacial Maximum and mid-Holocene, *Clim. Past*, 9, 811–823, <https://doi.org/10.5194/cp-9-811-2013>, 2013.
- Harrison, S. P., Bartlein, P. J., Brewer, S., Prentice, I. C., Boyd, M., Hessler, I., Holmgren, K., Izumi, K., and Willis, K.: Climate model benchmarking with glacial and mid-Holocene climates, *Clim. Dynam.*, 43, 671–688, 2014.
- Harrison, S. P., Bartlein, P. J., Izumi, K., Li, G., Annan, J., Hargreaves, J., Braconnot, P., and Kageyama, M.: Evaluation of CMIP5 palaeo-simulations to improve climate projections, *Nat. Clim. Change* 5, 735–743, <https://doi.org/10.1038/nclimate2649>, 2015.
- Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V., Brönnimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M., and Zhai, P. M.: Observations: Atmosphere and Surface, in: *Climate Change 2013, The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
- Haywood, A. M., Hill, D. J., Dolan, A. M., Otto-Bliesner, B. L., Bragg, F., Chan, W.-L., Chandler, M. A., Contoux, C., Dowsett, H. J., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Abe-Ouchi, A., Pickering, S. J., Ramstein, G., Rosenbloom, N. A., Salzmann, U., Sohl, L., Stepanek, C., Ueda, H., Yan, Q., and Zhang, Z.: Large-scale features of Pliocene climate: results from the Pliocene Model Intercomparison Project, *Clim. Past*, 9, 191–209, <https://doi.org/10.5194/cp-9-191-2013>, 2013.
- Haywood, A. M., Dowsett, H. J., Dolan, A. M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M. A., Hunter, S. J., Lunt, D. J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design, *Clim. Past*, 12, 663–675, <https://doi.org/10.5194/cp-12-663-2016>, 2016.
- Hessler, I., Harrison, S. P., Kucera, M., Waelbroeck, C., Chen, M.-T., Anderson, C., de Vernal, A., Fréchet, B., Cloke-Hayes, A., Leduc, G., and Londeix, L.: Implication of methodological uncertainties for mid-Holocene sea surface temperature reconstructions, *Clim. Past*, 10, 2237–2252, <https://doi.org/10.5194/cp-10-2237-2014>, 2014.
- Hind, A. and Moberg, A.: Past millennium solar forcing magnitude. A statistical hemispheric-scale climate model versus proxy data comparison, *Clim. Dynam.*, 41, 2527–2537, <https://doi.org/10.1007/s00382-012-1526-6>, 2013.
- Hopcroft, P. O. and Valdes, P. J.: Last Glacial Maximum constraints on the Earth System Model HadGEM2-ES, *Clim. Dynam.*, 45, 1657–1672, <https://doi.org/10.1007/s00382-014-2421-0>, 2015a.
- Hopcroft, P. O. and Valdes, P. J.: How well do simulated last glacial maximum tropical temperatures constrain equilibrium climate sensitivity?, *Geophys. Res. Lett.*, 42, 5533–5539, <https://doi.org/10.1002/2015GL064903>, 2015b.
- Hopcroft, P. O., Valdes, P. J., Woodward, S., and Joshi, M.: Last glacial maximum radiative forcing from mineral dust aerosols in an Earth System model, *J. Geophys. Res.*, 120, 8186–8205, <https://doi.org/10.1002/2015JD023742>, 2015.
- Ivanovic, R. F., Gregoire, L. J., Kageyama, M., Roche, D. M., Valdes, P. J., Burke, A., Drummond, R., Peltier, W. R., and Tarasov, L.: Transient climate simulations of the deglaciation 21–9 thousand years before present (version 1) – PMIP4 Core experiment design and boundary conditions, *Geosci. Model Dev.*, 9, 2563–2587, <https://doi.org/10.5194/gmd-9-2563-2016>, 2016.
- Izumi, K., Bartlein, P. J., and Harrison, S. P.: Consistent large-scale temperature responses in warm and cold climates, *Geophys. Res. Lett.*, 40, 1817–1823, <https://doi.org/10.1002/grl.50350>, 2013.
- Izumi, K., Bartlein, P. J., and Harrison, S. P.: Energy-balance mechanisms underlying consistent large-scale temperature responses in warm and cold climates, *Clim. Dynam.*, 44, 3111–3127, <https://doi.org/10.1007/s00382-014-2189-2>, 2015.
- Jones, C. D., Arora, V., Friedlingstein, P., Bopp, L., Brovkin, V., Dunne, J., Graven, H., Hoffmann, F., Ilyina, T., John, J. G., Jung, M., Kawamiya, M., Koven, C., Pongratz, J., Raddatz, T., Randerson, J. T., and Zaehle, S.: C4MIP – The Coupled Climate–Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6, *Geosci. Model Dev.*, 9, 2853–2880, <https://doi.org/10.5194/gmd-9-2853-2016>, 2016.
- Joussaume, S. and Braconnot, P.: Sensitivity of paleoclimate simulation results to season definitions, *J. Geophys. Res.-Atmos.*, 102, 1943–1956, 1997.
- Joussaume, S., Taylor, K. E., Braconnot, P., Mitchell, J. F. B., Kutzbach, J. E., Harrison, S. P., Prentice, I. C., Broccoli, A. J., Abe-Ouchi, A., Bartlein, P. J., Bonfils, C., Dong, B., Guiot, J., Herterich, K., Hewitt, C. D., Jolly, D., Kim, J. W., Kislov, A., Kitoh, A., Loutre, M. F., Masson, V., McAvaney, B., McFarlane, N., de Noblet, N., Peltier, W. R., Peterschmitt, J. Y., Pollard, D., Rind, D., Royer, J. F., Schlesinger, M. E., Syktus, J., Thompson, S., Valdes, P., Vettoretti, G., Webb, R. S., and Wypulla, U.: Monsoon Changes for 6000 Years Ago: Results of 18 Simulations from the Paleoclimate Modeling Intercomparison Project (PMIP), *Geophys. Res. Lett.*, 26, 859–862, 1999.
- Jungclaus, J. H., Bard, E., Baroni, M., Braconnot, P., Cao, J., Chini, L. P., Egorova, T., Evans, M., González-Rouco, J. F., Goosse, H., Hurrett, G. C., Joos, F., Kaplan, J. O., Khodri, M., Klein Goldewijk, K., Krivova, N., LeGrande, A. N., Lorenz, S. J., Luterbacher, J., Man, W., Maycock, A. C., Meinshausen, M., Moberg, A., Muscheler, R., Nehrbass-Ahles, C., Otto-Bliesner, B. I., Phipps, S. J., Pongratz, J., Rozanov, E., Schmidt, G. A., Schmidt, H., Schmutz, W., Schurer, A., Shapiro, A. I., Sigl, M., Smerdon, J. E., Solanki, S. K., Timmreck, C., Toohey, M., Usoskin, I. G., Wagner, S., Wu, C.-J., Yeo, K. L., Zanchettin, D., Zhang, Q., and Zorita, E.: The PMIP4 contribution to CMIP6 – Part 3: The last millennium, scientific objective, and experimental design for

- the PMIP4 past1000 simulations, *Geosci. Model Dev.*, 10, 4005–4033, <https://doi.org/10.5194/gmd-10-4005-2017>, 2017.
- Kageyama, M., Braconnot, P., Bopp, L., Mariotti, V., Roy, T., Woillez, M.-N., Caubel, A., Foujols, M.-A., Guilyardi, E., Khodri, M., Lloyd, J., Lombard, F., and Marti, O.: Mid-Holocene and Last Glacial Maximum climate simulations with the IPSL model. Part II: model-data comparisons, *Clim. Dynam.*, 40, 2469–2495, <https://doi.org/10.1007/s00382-012-1499-5>, 2013.
- Kageyama, M., Albani, S., Braconnot, P., Harrison, S. P., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Marti, O., Peltier, W. R., Peterschmitt, J.-Y., Roche, D. M., Tarasov, L., Zhang, X., Brady, E. C., Haywood, A. M., LeGrande, A. N., Lunt, D. J., Mahowald, N. M., Mikolajewicz, U., Nisancioglu, K. H., Otto-Bliesner, B. L., Renssen, H., Tomas, R. A., Zhang, Q., Abe-Ouchi, A., Bartlein, P. J., Cao, J., Li, Q., Lohmann, G., Ohgaito, R., Shi, X., Volodin, E., Yoshida, K., Zhang, X., and Zheng, W.: The PMIP4 contribution to CMIP6 – Part 4: Scientific objectives and experimental design of the PMIP4-CMIP6 Last Glacial Maximum experiments and PMIP4 sensitivity experiments, *Geosci. Model Dev.*, 10, 4035–4055, <https://doi.org/10.5194/gmd-10-4035-2017>, 2017.
- Karamperidou, C., Di Nezio, P. N., Timmermann, A., Jin, F. F., and Cobb, K. M.: The response of ENSO flavors to mid-Holocene climate: implications for proxy interpretation, *Paleoceanography*, 30, 527–547, 2015.
- Kohfeld, K., Le Quéré, C., Harrison, S. P., and Anderson, R. F.: Role of Marine Biology in Glacial-Interglacial CO₂ Cycles, *Science*, 308, 74–78, 2005.
- Kohfeld, K. E. and Harrison, S. P.: DIRTMAP: the geological record of dust, *Earth-Sci. Rev.*, 54, 81–114, 2001.
- Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D., and Rahmstorf, S.: Temperature-driven global sea-level variability in the Common Era, *P. Natl. Acad. Sci. USA*, 113, E1434–E1441, 2016.
- Krantz, D. E.: A chronology of Pliocene sea-level fluctuations: The U.S. Middle Atlantic Coastal Plain record, *Quaternary Sci. Rev.*, 10, 163–174, 1991.
- Kurschner, W. M., vanderBurgh, J., Visscher, H., and Dilcher, D. L.: Oak leaves as biosensors of late Neogene and early Pleistocene paleoatmospheric CO₂ concentrations, *Mar. Micropaleontol.*, 27, 299–312, 1996.
- Kutzbach, J. E. and Gallimore, R. G.: Sensitivity of a coupled atmosphere/mixed layer ocean model to changes in orbital forcing at 9000 years BP, *J. Geophys. Res.*, 93, 803–821, 1988.
- Laepple, T. and Huybers, P. J.: Global and regional variability in marine surface temperatures, *Geophys. Res. Lett.*, 41, 2528–2534, <https://doi.org/10.1002/2014GL059345>, 2014.
- Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambridge, M.: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, *P. Natl. Acad. Sci. USA*, 111, 15296–15303, 2014.
- Lambert, F., Tagliabue, A., Shaffer, G., Lamy, F., Winckler, G., Farias, L., Gallardo, L., and De Pol-Holz, R.: Dust fluxes and iron fertilization in Holocene and Last Glacial Maximum climates, *Geophys. Res. Lett.*, 42, 6014–6023, <https://doi.org/10.1002/2015GL064250>, 2015.
- Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., and Levrard, B.: A long-term numerical solution for the insolation quantities of the Earth, *Astro. Astrophys.*, 428, 261–285, 2004.
- Lawrence, D. M., Hurtt, G. C., Arneth, A., Brovkin, V., Calvin, K. V., Jones, A. D., Jones, C. D., Lawrence, P. J., de Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S. I., and Shevliakova, E.: The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design, *Geosci. Model Dev.*, 9, 2973–2998, <https://doi.org/10.5194/gmd-9-2973-2016>, 2016.
- Li, G., Harrison, S. P., Izumi, K., and Prentice, I. C.: Precipitation scaling with temperature in warm and cold climates: an analysis of CMIP5 simulations, *Geophys. Res. Lett.*, 40, 4018–4024, <https://doi.org/10.1002/grl.50730>, 2013.
- Li, G., Harrison, S. P., Prentice, I. C., and Falster, D.: Simulation of tree-ring widths with a model for primary production, carbon allocation, and growth, *Biogeosciences*, 11, 6711–6724, <https://doi.org/10.5194/bg-11-6711-2014>, 2014.
- Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic delta O-18 records, *Paleoceanography*, 20, PA1003, <https://doi.org/10.1029/2004PA001071>, 2005.
- Liu, Z., Lu, Z., Wen, X., Otto-Bliesner, B. L., Timmermann, A., and Cobb, K. M.: Evolution and forcing mechanisms of El Niño over the past 21,000 years, *Nature*, 515, 550–553, <https://doi.org/10.1038/nature13963>, 2014.
- Lombard, F., Labeyrie, L., Michel, E., Bopp, L., Cortijo, E., Retailleau, S., Hwa, H., and Jorissen, F.: Modelling planktic foraminifer growth and distribution using an ecophysiological multi-species approach, *Biogeosciences*, 8, 853–873, <https://doi.org/10.5194/bg-8-853-2011>, 2011.
- Luan, Y. H., Braconnot, P., Yu, Y. Q., and Zheng, W. P.: Tropical Pacific mean state and ENSO changes: sensitivity to freshwater flux and remnant ice sheets at 9.5 ka BP, *Clim. Dynam.*, 44, 661–678, 2015.
- Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.-M., Raynaud, D., Stocker, T. F., and Chappellaz, J.: Orbital and millennial-scale features of atmospheric CH₄ over the past 800,000 years, *Nature*, 453, 383–386, <https://doi.org/10.1038/nature06950>, 2008.
- Lunt, D. J., Dunkley Jones, T., Heinemann, M., Huber, M., LeGrande, A., Winguth, A., Loptson, C., Marotzke, J., Roberts, C. D., Tindall, J., Valdes, P., and Winguth, C.: A model-data comparison for a multi-model ensemble of early Eocene atmosphere–ocean simulations: EoMIP, *Clim. Past*, 8, 1717–1736, <https://doi.org/10.5194/cp-8-1717-2012>, 2012.
- Lunt, D. J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J. H., Khon, V. C., Krebs-Kanzow, U., Langebroek, P. M., Lohmann, G., Nisancioglu, K. H., Otto-Bliesner, B. L., Park, W., Pfeiffer, M., Phipps, S. J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E. J., Takahashi, K., Wei, W., Yin, Q., and Zhang, Z. S.: A multi-model assessment of last interglacial temperatures, *Clim. Past*, 9, 699–717, <https://doi.org/10.5194/cp-9-699-2013>, 2013.
- Lunt, D. J., Huber, M., Anagnostou, E., Baatsen, M. L. J., Caballero, R., DeConto, R., Dijkstra, H. A., Donnadieu, Y., Evans, D., Feng, R., Foster, G. L., Gasson, E., von der Heydt, A. S., Hollis, C. J., Inglis, G. N., Jones, S. M., Kiehl, J., Kirtland Turner, S., Korty, R. L., Kozdon, R., Krishnan, S., Ladant, J.-B., Langebroek, P., Lear,

- C. H., LeGrande, A. N., Littler, K., Markwick, P., Otto-Bliesner, B., Pearson, P., Poulsen, C. J., Salzmann, U., Shields, C., Snell, K., Stärr, M., Super, J., Tabor, C., Tierney, J. E., Tourte, G. J. L., Tripathi, A., Upchurch, G. R., Wade, B. S., Wing, S. L., Winguth, A. M. E., Wright, N. M., Zachos, J. C., and Zeebe, R. E.: The DeepMIP contribution to PMIP4: experimental design for model simulations of the EECO, PETM, and pre-PETM (version 1.0), *Geosci. Model Dev.*, 10, 889–901, <https://doi.org/10.5194/gmd-10-889-2017>, 2017.
- Lynch-Stieglitz, J., Adkins, J. F., Curry, W. B., Dokken, T., Hall, I. R., Herguera, J. C., Hirschi, J. J. M., Ivanova, E. V., Kissel, C., Marchal, O., Marchitto, T. M., McCave, I. N., McManus, J. F., Mulitza, S., Ninnemann, U., Peeters, F., Yu, E. F., and Zahn, R.: Atlantic meridional overturning circulation during the Last Glacial Maximum, *Science*, 316, 66–69, 2007.
- Maher, B., Prospero, J. M., Mackie, D., Gaiero, D., Hesse, P. P., and Balkanski, Y.: Global connections between aeolian dust, climate and ocean biogeochemistry at the present day and at the last glacial maximum, *Earth-Sci. Rev.*, 99, 61–97, 2010.
- Man, W., Zhou, T., and Jungclaus, J. H.: Simulation of the East Asian Summer Monsoon during the Last Millennium with the MPI Earth System Model, *J. Climate*, 25, 7852–7866, 2012.
- Man, W., Zhou, T., and Jungclaus, J. H.: Effects of large volcanic eruptions on global summer climate and East Asian Monsoon changes during the Last Millennium: Analysis of MPI-ESM simulations, *J. Climate*, 27, 7394–7409, 2014.
- Man, W. M. and Zhou, T. J.: Regional-scale surface air temperature and East Asian summer monsoon changes during the last millennium simulated by the FGOALS-gl climate system model, *Adv. Atmos. Sci.*, 31, 765–778, 2014.
- Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, *Science*, 326, 1256–1260, <https://doi.org/10.1126/science.1177303>, 2009.
- Marcott, S. A., Bauska, T. K., Buizert, C., Steig, E. J., Rosen, J. L., Cuffey, K. M., Fudge, T. J., Severinghaus, J. P., Ahn, J., Kalk, M. L., McConnell, J. R., Sowers, T., Taylor, K. C., White, J. W. C., and Brook, E. J.: Centennial-scale changes in the global carbon cycle during the last deglaciation, *Nature*, 514, 616–619, <https://doi.org/10.1038/nature13799>, 2014.
- MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, *Nat. Geosci.*, 2, 127–132, 2009.
- Marzocchi, A. and Jansen, M. F.: Connecting Antarctic sea ice to deep-ocean circulation in modern and glacial climate simulations, *Geophys. Res. Lett.*, 44, 6286–6295, <https://doi.org/10.1002/2017GL073936>, 2017.
- Masson-Delmotte, V., Kageyama, M., Braconnot, P., Charbit, S., Krinner, G., Ritz, C., Guilyardi, E., Hoffmann, G., Jouzel, J., Abe-Ouchi, A., Crucifix, M., Gladstone, R. M., Hewitt, C. D., Kitoh, A., Legrande, A., Marti, O., Merkel, U., Motoi, T., Ohgaito, R., Otto-Bliesner, B., Peltier, W. R., Ross, I., Valdes, P. J., Vettoretti, G., Weber, S. L., and Wolk, F.: Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints, *Clim. Dynam.*, 26, 513–529, <https://doi.org/10.1007/s00382-005-0081-9>, 2006.
- Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., González Rouco, J. F., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X., and Timmermann, A.: Information from Paleoclimatic archives, in: *Climate Change 2013: The physical basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
- McGee, D., deMenocal, P. B., Winckler, G., Stuut, J. B. W., and Bradtmiller, L. I.: The magnitude, timing and abruptness of changes in North African dust deposition over the last 20,000yr, *Earth Planet. Sc. Lett.*, 371–372, 163–176, <https://doi.org/10.1016/j.epsl.2013.03.054>, 2013.
- Miller, K. G., Wright, J. D., Browning, J. V., Kulpecz, A., Kominz, M., Naish, T. R., Cramer, B. S., Rosenthal, Y., Peltier, W. R., and Soudrian, S.: High tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation, *Geology*, 40, G32869, <https://doi.org/10.1130/G32869.1>, 2012.
- Naish, T. R. and Wilson, G. S.: Constraints on the amplitude of Mid-Pliocene (3.6–2.4 Ma) eustatic sea-level fluctuations from the New Zealand shallow-marine sediment record, *Philos. T. Roy. Soc. A*, 367, 169–187, 2009.
- Notz, D., Jahn, A., Holland, M., Hunke, E., Massonnet, F., Stroeve, J., Tremblay, B., and Vancoppenolle, M.: The CMIP6 Sea-Ice Model Intercomparison Project (SIMIP): understanding sea ice through climate-model simulations, *Geosci. Model Dev.*, 9, 3427–3446, <https://doi.org/10.5194/gmd-9-3427-2016>, 2016.
- Nowicki, S. M. J., Payne, A., Larour, E., Seroussi, H., Goelzer, H., Lipscomb, W., Gregory, J., Abe-Ouchi, A., and Shepherd, A.: Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6, *Geosci. Model Dev.*, 9, 4521–4545, <https://doi.org/10.5194/gmd-9-4521-2016>, 2016.
- Otto-Bliesner, B., Brady, E., Fasullo, J., Jahn, A., Landrum, L., Stevenson, S., Rosenbloom, N., Mai, A., and Strand, G.: Climate Variability and Change since 850 C.E.: An Ensemble Approach with the Community Earth System Model (CESM), *B. Am. Meteorol. Soc.*, 97, 735–754, <https://doi.org/10.1175/BAMS-D-14-00233.1>, 2016.
- Otto-Bliesner, B. L., Braconnot, P., Harrison, S. P., Lunt, D. J., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Capron, E., Carlson, A. E., Dutton, A., Fischer, H., Goelzer, H., Govin, A., Haywood, A., Joos, F., LeGrande, A. N., Lipscomb, W. H., Lohmann, G., Mahowald, N., Nehrbass-Ahles, C., Pausata, F. S. R., Peterschmitt, J.-Y., Phipps, S. J., Renssen, H., and Zhang, Q.: The PMIP4 contribution to CMIP6 – Part 2: Two interglacials, scientific objective and experimental design for Holocene and Last Interglacial simulations, *Geosci. Model Dev.*, 10, 3979–4003, <https://doi.org/10.5194/gmd-10-3979-2017>, 2017.
- Pagani, M., Liu, Z. H., LaRiviere, J., and Ravelo, A. C.: High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations, *Nat. Geosci.*, 3, 27–30, 2010.
- PAGES2k Consortium: Ahmed, M., Anchukaitis, K. J., Asrat, A., Borgaonkar, H. P., Braida, M., Buckley, B. M., Büntgen, U., Chase, B. M., Christie, D. A., Cook, E. R., Curran, M. A. J., Diaz, H. F., Esper, J., Fan, Z.-X., Gaire, N. P., Ge, Q., Gergis, J., González-Rouco, J. F., Goosse, H., Grab, S. W., Graham, N., Graham, R., Grosjean, M., Hanhijärvi, S. T., Kaufman, D. S., Kiefer, T., Kimura, K., Korhola, A. A., Krusic, P. J., Lara, A.,

- Lézine, A.-M., Ljungqvist, F. C., Lorrey, A. M., Luterbacher, J., Masson-Delmotte, V., McCarroll, D., McConnell, J. R., McKay, N. P., Morales, M. S., Moy, A. D., Mulvaney, R., Mundo, I. A., Nakatsuka, T., Nash, D. J., Neukom, R., Nicholson, S. E., Oerter, H., Palmer, J. G., Phipps, S. J., Prieto, M. R., Rivera, A., Sano, M., Severi, M., Shanahan, T. M., Shao, X., Shi, F., Sigl, M., Smerdon, J. E., Solomina, O. N., Steig, E. J., Stenni, B., Thamban, M., Trouet, V., Turney, C. S. M., Umer, M., van Ommen, T., Verschuren, D., Viau, A. E., Villalba, R., Vinther, B. M., von Gunten, L., Wagner, S., Wahl, E. R., Wanner, H., Werner, J. P., White, J. W. C., Yasue, K., and Zorita, E.: Continental-scale temperature variability during the last two millennia, *Nat. Geosci.*, 6, 339–346, 2013.
- PAGES 2k-PMIP3 group: Continental-scale temperature variability in PMIP3 simulations and PAGES 2k regional temperature reconstructions over the past millennium, *Clim. Past*, 11, 1673–1699, <https://doi.org/10.5194/cp-11-1673-2015>, 2015.
- PALAEOSSENS Project Members: Making sense of palaeoclimate sensitivity, *Nature*, 491, 683–691, <https://doi.org/10.1038/nature11574>, 2012.
- Pausata, F. S. R., Messori, G., and Zhang, Q.: Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period, *Earth Planet. Sc. Lett.*, 434, 298–307, <https://doi.org/10.1016/j.epsl.2015.11.049>, 2016.
- Peltier, W. R., Argus, D. F., and Drummond, R.: Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model, *J. Geophys. Res.-Sol. Ea.*, 120, 450–487, <https://doi.org/10.1002/2014JB011176>, 2015.
- Perez-Sanz, A., Li, G., González-Sampériz, P., and Harrison, S. P.: Evaluation of modern and mid-Holocene seasonal precipitation of the Mediterranean and northern Africa in the CMIP5 simulations, *Clim. Past*, 10, 551–568, <https://doi.org/10.5194/cp-10-551-2014>, 2014.
- Phipps, S. J., McGregor, H. V., Gergis, J., Gallant, A. J., Neukom, R., Stevensons, S., and Van Ommen, T. D.: Paleoclimate data-model comparison and the role of climate forcings over the past 1500 years, *J. Climate*, 26, 6915–6936, <https://doi.org/10.1175/JCLI-D-12-00108.1>, 2013.
- Pincus, R., Forster, P. M., and Stevens, B.: The Radiative Forcing Model Intercomparison Project (RFMIP): experimental protocol for CMIP6, *Geosci. Model Dev.*, 9, 3447–3460, <https://doi.org/10.5194/gmd-9-3447-2016>, 2016.
- Pollard, D. and Reusch, D. B.: A calendar conversion method for monthly mean paleoclimate model output with orbital forcing, *J. Geophys. Res.-Atmos.*, 107, ACL 3-1–ACL 3-7, 2002.
- Prentice, I. C., Kelley, D. I., Foster, P. N., Friedlingstein, P., Harrison, S. P., and Bartlein, P. J.: Modeling fire and the terrestrial carbon balance, *Global Biogeochem. Cy.*, 25, GB3005, <https://doi.org/10.1029/2010GB003906>, 2011.
- Raymo, M. E., Grant, B., Horowitz, M., and Rau, G. H.: Mid-Pliocene warmth: Stronger greenhouse and stronger conveyor, *Mar. Micropaleontol.*, 27, 313–326, 1996.
- Raymo, M. E., Hearty, P., De Conto, R., O' Leary, M., Dowsett, H. J., Robinson, M. M., and Mitrovica, J. X.: PLIOMAX: Pliocene maximum sea level project, *PAGES News*, 17, 58–59, 2009.
- Roche, D. M., Crosta, X., and Renssen, H.: Evaluating Southern Ocean sea-ice for the Last Glacial Maximum and pre-industrial climates: PMIP-2 models and data evidence, *Quaternary Sci. Rev.*, 56, 99–106, 2012.
- Rohling, E. J., Foster, G. L., Grant, K. M., Marino, G., Roberts, A. P., Tamisiea, M. E., and Williams, F.: Sea-level and deep-sea-temperature variability over the past 5.3 million years, *Nature*, 508, 477–482, 2014.
- Saint-Lu, M., Braconnot, P., Leloup, J., Lengaigne, M., and Marti, O.: Changes in the ENSO/SPCZ relationship from past to future climates, *Earth Planet. Sc. Lett.*, 412, 18–24, <https://doi.org/10.1016/j.epsl.2014.12.033>, 2015.
- Salzmänn, U., Haywood, A. M., Lunt, D. J., Valdes, P. J., and Hill, D. J.: A new global biome reconstruction and data-model comparison for the Middle Pliocene, *Global Ecol. Biogeogr.*, 17, 432–447, 2008.
- Salzmänn, U., Dolan, A. M., Haywood, A. M., Chan, W.-L., Hill, D. J., Abe-Ouchi, A., Otto-Bliesner, B., Bragg, F., Chandler, M. A., Contoux, C., Dowsett, H. J., Jost, A., Kamae, Y., Lohmann, Lunt, D. J., Pickering, S. J., Pound, M. J., Ramstein, G., Rosenbloom, N. A., Sohl, L., Stepanek, C., Ueda, H., and Zhang, Z.: Challenges in reconstructing terrestrial warming of the Pliocene revealed by data-model discord, *Nat. Clim. Change*, 3, 969–974, 2013.
- Schmidt, G. A., Jungclauss, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0), *Geosci. Model Dev.*, 4, 33–45, <https://doi.org/10.5194/gmd-4-33-2011>, 2011.
- Schmidt, G. A., Jungclauss, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), *Geosci. Model Dev.*, 5, 185–191, <https://doi.org/10.5194/gmd-5-185-2012>, 2012.
- Schurer, A. P., Tett, S. F. B., and Hegerl, G. C.: Small influence of solar variability on climate over the last millennium, *Nat. Geosci.*, 7, 104–108, <https://doi.org/10.1038/NGEO2-40>, 2014.
- Seki, O., Foster, G. L., Schmidt, D. N., Mackensen, A., Kawamura, K., and Pancost, R. D.: Alkenone and boron-based Pliocene pCO₂ records, *Earth Planet. Sc. Lett.*, 292, 201–211, 2010.
- Sherwood, S. C., Bony, S., and Dufresne, J. L.: Spread in model climate sensitivity traced to atmospheric convective mixing, *Nature*, 505, 37–42, 2014.
- Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O. J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D. R., Pilcher, J. R., Salzer, M., Schüpbach, S., Steffensen, J. P., Vinther, B. M., and Woodruff, T. E.: Timing and climate forcing of volcanic eruptions for the past 2,500 years, *Nature*, 523, 543–549, <https://doi.org/10.1038/nature14565>, 2015.
- Spratt, R. M. and Lisiecki, L. E.: A Late Pleistocene sea level stack, *Clim. Past*, 12, 1079–1092, <https://doi.org/10.5194/cp-12-1079-2016>, 2016.
- Stap, L. B., de Boer, B., Ziegler, M., Bintanja, R., Lourens, L. J., and van de Wal, R. S. W.: CO₂ over the past 5 million years: Continuous simulation and new $\delta^{11}\text{B}$ -based proxy data, *Earth Planet. Sc. Lett.*, 439, 1–10, 2016.

- Steffensen, J. P., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S. J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S. O., Rothlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M. L., Sveinbjornsdottir, A. E., Svensson, A., and White, J. W. C.: High-Resolution Greenland Ice Core Data Show Abrupt Climate Change Happens in Few Years, *Science*, 321, 680–684, 2008.
- Steig, E. J., Huybers, K., Singh, H. A., Steiger, N. J., Ding, Q. H., Frierson, D. M. W., Popp, T., and White, J. W. C.: Influence of West Antarctic Ice Sheet collapse on Antarctic surface climate, *Geophys. Res. Lett.*, 42, 4862–4868, 2015.
- Tarasov, L., Dyke, A. S., Neal, R. M., and Peltier, W. R.: A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling, *Earth Planet. Sc. Lett.*, 315–316, 30–40, <https://doi.org/10.1016/j.epsl.2011.09.010>, 2012.
- Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the experiment design, *B. Am. Meteorol. Soc.*, 93, 485–498, <https://doi.org/10.1175/BAMS-D-11-00094.1>, 2012.
- Timm, O., Timmermann, A., Abe-Ouchi, A., Saito, F., and Segawa, T.: On the definition of seasons in paleoclimate simulations with orbital forcing, *Paleoceanography*, 23, PA2221, <https://doi.org/10.1029/2007PA001461>, 2008.
- Tripathi, A. K., Roberts, C. D., and Eagle, R. A.: Coupling of CO₂ and Ice Sheet Stability Over Major Climate Transitions of the Last 20 Million Years, *Science*, 326, 1394–1397, 2009.
- Turney, C. S. M. and Jones, R. T.: Does the Agulhas Current amplify global temperatures during super-interglacials?, *J. Quaternary Sci.*, 25, 839–843, <https://doi.org/10.1002/jqs.1423>, 2010.
- van den Hurk, B., Kim, H., Krinner, G., Seneviratne, S. I., Derksen, C., Oki, T., Douville, H., Colin, J., Ducharne, A., Cheruy, F., Viovy, N., Puma, M. J., Wada, Y., Li, W., Jia, B., Alessandri, A., Lawrence, D. M., Weedon, G. P., Ellis, R., Hagemann, S., Mao, J., Flanner, M. G., Zampieri, M., Materia, S., Law, R. M., and Sheffield, J.: LS3MIP (v1.0) contribution to CMIP6: the Land Surface, Snow and Soil moisture Model Intercomparison Project – aims, setup and expected outcome, *Geosci. Model Dev.*, 9, 2809–2832, <https://doi.org/10.5194/gmd-9-2809-2016>, 2016.
- Wardlaw, B. R. and Quinn, T. M.: The record of Pliocene sea-level change at Enewetak Atoll, *Quaternary Sci. Rev.*, 10, 247–258, 1991.
- Webb, M. J., Andrews, T., Bodas-Salcedo, A., Bony, S., Bretherton, C. S., Chadwick, R., Chepfer, H., Douville, H., Good, P., Kay, J. E., Klein, S. A., Marchand, R., Medeiros, B., Siebesma, A. P., Skinner, C. B., Stevens, B., Tselioudis, G., Tsushima, Y., and Watanabe, M.: The Cloud Feedback Model Intercomparison Project (CFMIP) contribution to CMIP6, *Geosci. Model Dev.*, 10, 359–384, <https://doi.org/10.5194/gmd-10-359-2017>, 2017.
- Winsor, K., Carlson, A. E., Klinkhammer, G. P., Stoner, J. S., and Hatfield, R. G.: Evolution of the northeast Labrador Sea during the last interglaciation, *Geochem. Geophys. Geos.*, 13, Q11006, <https://doi.org/10.1029/2012GC004263>, 2012.
- Wittenberg, A. T.: Are historical records sufficient to constrain ENSO simulations?, *Geophys. Res. Lett.*, 36, L12702, <https://doi.org/10.1029/2009GL038710>, 2009.
- Yoshimori, M., Hargreaves, J. C., Annan, J. D., Yokohata, T., and Abe-Ouchi, A.: Dependency of feedbacks on forcing and climate state in physics parameter ensembles, *J. Climate*, 24, 6440–6455, 2011.
- Zanchettin, D., Khodri, M., Timmreck, C., Toohey, M., Schmidt, A., Gerber, E. P., Hegerl, G., Robock, A., Pausata, F. S. R., Ball, W. T., Bauer, S. E., Bekki, S., Dhomse, S. S., LeGrande, A. N., Mann, G. W., Marshall, L., Mills, M., Marchand, M., Niemeier, U., Poulain, V., Rozanov, E., Rubino, A., Stenke, A., Tsigaridis, K., and Tummon, F.: The Model Intercomparison Project on the climatic response to Volcanic forcing (VolMIP): experimental design and forcing input data for CMIP6, *Geosci. Model Dev.*, 9, 2701–2719, <https://doi.org/10.5194/gmd-9-2701-2016>, 2016.
- Zhang, R., Yan, Q., Zhang, Z. S., Jiang, D., Otto-Bliesner, B. L., Haywood, A. M., Hill, D. J., Dolan, A. M., Stepanek, C., Lohmann, G., Contoux, C., Bragg, F., Chan, W.-L., Chandler, M. A., Jost, A., Kamae, Y., Abe-Ouchi, A., Ramstein, G., Rosenbloom, N. A., Sohl, L., and Ueda, H.: Mid-Pliocene East Asian monsoon climate simulated in the PlioMIP, *Clim. Past*, 9, 2085–2099, <https://doi.org/10.5194/cp-9-2085-2013>, 2013.
- Zheng, W. and Braconnot, P.: Characterization of model spread in PMIP2 Mid-Holocene simulations of the African Monsoon, *J. Climate*, 26, 1192–1210, 2013.
- Zheng, W., Braconnot, P., Guilyardi, E., Merkel, U., and Yu, Y.: ENSO at 6 ka and 21 ka from ocean-atmosphere coupled model simulations, *Clim. Dynam.*, 30, 745–762, <https://doi.org/10.1007/s00382-007-0320-3>, 2008.